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PATHOGEN RISK ASSESSMENT FOR LAND APPLICATION OF MUNICIPAL SLUDGE. VOLUME I: METHODOLOGY AND COMPUTER MODEL

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Section 405 of the Clean Water Act requires the U.S. EPA to develop and issue regulations that identify: 1) uses for sludge including disposal; 2) specific factors (including costs) to be taken into account in determining the measures and practices applicable for each use or disposal; and 3) concentrations of pollutants that interfere with each use or disposal. To comply with this mandate, the U.S. EPA has embarked on a program to develop four major technical regulations: land application, including distribution and marketing; landfilling; incineration and surface disposal. The develop of these technical regulations requires a consideration of pathogens as well as chemical constituents of sludge. The purpose of this report is to describe a proposed methodology and associated computer model designed to assess the potential risks to human health posed by pathogens in municipal sewage sludge applied to land as fertilizer or soil conditioner. Volume I: Methodology and Computer Model describes the conceptual framework of the risk assessment methodology and the structural organization, including assumptions and components, of the computer model. Volume II: User's Manual contains background information to provide the user with an understanding of the actual functioning of the model. This information includes descriptions of operating variables and their default values, explanations of the various subroutines, and the mathematical basis for process and transfer functions.

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PREFACE

Section 405 of the Clean Water Act requires the U.S. Environmental Protection Agency to develop and issue regulations that identify: (1) uses for sludge including disposal; (2) specific factors (including costs) to be taken into account in determining the measures and practices applicable for each use or disposal; and (3) concentrations of pollutants that interfere with each use or disposal. To comply with this mandate, the U.S. EPA has embarked on a program to develop four major technical regulations: land application, including distribution and marketing; landfilling; incineration and surface disposal. The development of these technical regulations requires a consideration of pathogens as well as chemical constituents of sludge. Public concern related to the reuse and disposal of municipal sludge often focuses on the issue of pathogenic organisms. The purpose of this report is to describe a proposed methodology and associated computer model designed to assess the potential risks to human health posed by pathogens in municipal sewage sludge applied to land as fertilizer or soil conditioner.

Volume I: Methodology and Computer Model describes the conceptual framework of the risk assessment methodology and the structural organization, including assumptions and components, of the computer model. Volume II: User's Manual contains background information to provide the user with an understanding of the actual functioning of the model. This information includes descriptions of operating variables and their default values, explanations of the various subroutines, and the mathematical basis for process and transfer functions.

The first draft of this document was prepared by Science Applications International Corporation under a U.S. EPA Interagency Agreement with the Department of Energy. Portions of the document were also developed by the University of Cincinnati under a Cooperative Agreement with the U.S. EPA.

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1. EXECUTIVE SUMMARY

This document describes a methodology and associated computer model for assessing the risk to humans of pathogens in treated municipal sewage sludge applied to land. Land application of sludge in this methodology refers to the distribution of sludge on or just below the soil surface where it is employed as a fertilizer or soil conditioner for growing human food-chain and non-food-chain crops. The two categories of land application addressed in this model are (1) agricultural utilization and (2) distribution and marketing (D&M), and the source of microbial pathogens is (1) liquid or (2) dried or composted municipal sewage sludge.

The approach used for the model provides a structure capable of supporting both stochastic and deterministic mathematical relationships, i.e., it is a dynamic model that can incorporate site-specific data while allowing process functions to be dependent on environmental factors, such as temperature and rainfall. The model structure provides a flexibility that permits addition and/or deletion of sludge management practice compartments as well as modifications in process and transfer functions. The model is designed to run on a personal computer with a minimum of 540 KB of free memory. Currently limited by a lack of data, the model will be able to utilize data gathered in the future to enhance its predictive accuracy.

The purpose of the model is to determine the probability of infection of the human receptor from pathogens in the land-applied sludge. The ultimate objective is to use the model to assist EPA in its regulatory activities, but the immediate uses include (1) further development of the pathogen model as a research and risk assessment tool and (2) the application of the methodology in the performance of actual pathogen risk assessments.

The five municipal sewage sludge management practices addressed by the model are: application of liquid treated sludge (1) for production of commercial crops for human consumption, (2) to grazed pastures, and (3) for production of crops processed before animal consumption; and application of dried or composted sludge (4) to residential vegetable gardens and (5) to residential lawns.

The computer model represents the compartments and transfers among compartments of the five management practices. The compartments are the various locations, states or activities in which sludge or sludge-associated pathogens exist; they vary to some extent among practices. In each compartment, pathogens either increase, decrease or remain the same in number with time, as specified by "process functions" (growth, die-off or no population changes) and "transfer functions" (movement between compartments). The population in each compartment, therefore, generally varies with time and is determined by a combination of initial pathogen input, "transfer functions" and "process functions." The populations of pathogens in the compartments representing human exposure locations, together with appropriate intake and infective dose data, are used to estimate human health risk.

Considering modern disposal practices, almost any pathogenic organism can be found in municipal sewage. Because of the difficulty of designing a model that could accurately simulate the survival and environmental movement of more than a few microbial species, organisms or organism groups were selected to represent the enteric pathogens most commonly found in sludge. The current version of the model deals with only three of these selections: Salmonella spp. representing the bacteria; Ascaris lumbricoides, the parasites (both helminth worms and protozoa); and enteroviruses (a grouping of several animal viruses), the enteric viruses.

Exposure of an individual to enteric pathogens can lead to (1) no effect, (2) a subclinical (asymptomatic) infection or (3) a clinical (symptomatic) infection. Although subclinical infections are not clinically detectable, that individual by either direct or indirect transmission of the pathogenic organisms may cause disease to develop in others. In this methodology, infection rather than disease is used to measure risk.

Exposure pathways, i.e., migration routes of pathogens from or within the application or disposal site to a target organism or receptor, for sludge applied to land include the following:

- inhalation or ingestion of emissions from application of sludge or tilling of sludge/soil;
- inhalation or ingestion of windblown or mechanically generated particulates;
- swimming in a pond fed by surface water runoff;
- direct contact with sludge-contaminated soil or crops (including grass, vegetables, or forage crops);
- drinking water from an offsite well;
- inhalation and subsequent ingestion of aerosols from irrigation;
- consumption of vegetables grown in sludge-amended soil;
- consumption of meat or milk from cattle grazing on or consuming forage from sludge-amended fields.

Since the model provides only an approximation of environmental transport mechanisms, it does not represent every possible exposure pathway. It does, however, trace the flow of pathogens through the major routes leading to possible human exposure.

The dose required to cause infection is based on the virulence or infectivity of the pathogenic organism and on the susceptibility of the exposed population or individual receptor. The "minimum infective dose" or MID is typically the dose required to infect 50% of the population. The uncertainty in measuring infectious doses greatly weakens the power of any quantitative risk assessment. The model is designed, therefore, so that the user can supply a best estimate of infectious dose for the particular pathogen and practice being modeled.

Risk assessments ordinarily proceed from source to receptor. That is, the source, or sludge disposal/reuse practice, is first characterized, and contaminant movement away from the source is then modeled to estimate the degree of exposure to the human receptor. Health effects are then predicted based on the estimated exposure and dose-response relationships. This computer model sums the hourly exposures of a human receptor to pathogens in each exposure compartment and computes the daily (24-hour) probability of the human receptor receiving an exposure exceeding an infective dose (e.g., for Salmonella, the default MID=10).

Many factors contribute to the uncertainties associated with the present risk assessment model. Chief among these is the lack of quantitative data describing the processes involved. Even when available, data are highly variable with regard to (1) the initial concentrations of microbial pathogens in wastewater and sludge; (2) processes of microbial transport and inactivation; (3) dose-response relationships; and (4) exposure levels and receptor susceptibility.

A sensitivity analysis was performed, but because of the large number of input parameters and the uncertainty related to the values of parameters, it should be viewed as preliminary. However, the analysis does indicate that the model is very sensitive to the inactivation rate of microorganisms in soil, as well as to the parameters used to calculate the fractions of pathogens transferred from surface soil to subsurface soil, from subsurface soil to groundwater and from surface soil to surface runoff water. Accordingly, these parameters should be selected with great care, especially as they are all likely to be site-specific. Because the data available to support choices of the values are limited, research efforts should be directed to these areas in order to increase the accuracy of the model.

2. INTRODUCTION AND DESCRIPTION OF GENERAL APPROACH

2.1. PURPOSE AND SCOPE

This report is one of a series that presents methodologies for assessing the potential risks to humans or other organisms that may result from management practices for the disposal or reuse of municipal sewage sludge. The practices addressed by this series include land application, distribution and marketing programs (D&M), landfilling, incineration, ocean disposal and surface disposal. In particular, these reports discuss methods used to evaluate potential health and environmental risks from toxic chemicals or pathogenic organisms that may be present in sludge. This document considers only the land application of sludge, including its distribution and marketing, and assesses potential pathogen-induced health risks associated with this practice.

For the immediate future, the risk assessment methodology and accompanying model may serve to (1) contribute to the continued development of the risk assessment process for pathogens and (2) provide a working version of the model for performance of actual pathogen risk assessments. The risk assessment procedures presented in this report constitute one approach to evaluating technology-based sludge management options. Ultimately, these procedures may be used by the U.S. EPA Environmental Criteria and Assessment Office to help develop technical criteria for microbial pathogens in sludge, the initial effort being a prototype criteria document for bacteria. The methodology and model may also be useful in developing guidance for the selection of sludge management options by local authorities. These uses are not the focus of this document, however, and will not be discussed. Neither does this methodology address potential risks associated with the treatment, handling or storage of sludge, transportation to the point of reuse or disposal, or accidental release.

This study is based on the "Sewage Sludge Pathogen Transport Model Project" (U.S. EPA, 1980), undertaken to assess the risk from pathogens associated with the reuse/disposal of municipal sludges by the options of land application and D&M. Widely referred to as the "Sandia Model," the model and methodology were initially developed by the BDM Corporation in cooperation with Sandia National Laboratories and the U.S. Department of Energy, and they have been modified by the University of Cincinnati in cooperation with the U.S. EPA. Most recently, development has been continued by Science Applications International Corporation, Oak Ridge, TN, under contracts and an interagency agreement involving Analysas Corporation, the U.S. EPA and the U.S. Department of Energy.

2.2. DEFINITION AND COMPONENTS OF RISK ASSESSMENT

The 1983 National Academy of Sciences report (NRC, 1983) defines risk assessment as "the characterization of the potential adverse health effects of human exposures to environmental hazards." By contrast, risk management is defined as "the process of evaluating alternative regulatory actions and selecting among them." This selection is made through consideration of costs, available technology and other nonrisk factors. The National Academy of Sciences organized the risk assessment process into four components:

(1) hazard identification - "the process of determining whether exposure to an agent can cause an increase in the incidence of a health condition...."

(2) dose-response assessment - "the process of characterizing the relation between the dose of an agent...and the incidence of an adverse health effect in exposed populations and estimating the incidence of the effect as a function of human exposure to the agent."

(3) exposure assessment - "the process of measuring or estimating the intensity, frequency, and duration of human exposures to an agent...or of estimating hypothetical exposures that might arise...."

(4) risk characterization - "the process of estimating the incidence of a health effect...by combining the exposure and dose-response assessments." (NRC, 1983)

The U.S. EPA has broadened the definitions of hazard identification and dose-response assessment to include the nature and severity of the toxic effect in addition to the incidence (U.S. EPA, 1989a). This outline of the risk assessment process provides the framework for the description of the pathogen risk assessment methodology and model in this report.

2.3. RISK ASSESSMENT IN THE METHODOLOGY DEVELOPMENT PROCESS

The process of developing a risk assessment methodology begins by defining the management practice. Land application refers to the distribution of sludge on or just below the soil surface where it is employed (1) as a fertilizer or soil conditioner for growing human food-chain and non-food-chain crops, (2) in land reclamation or (3) to utilize the land as a sludge treatment system. Five categories of land application are recognized: agricultural utilization, forest land utilization, drastically disturbed land utilization, dedicated land disposal, and distribution and marketing (D&M). The last of these refers to the giveaway or sale of bulk or bagged sludge or sludge products to the public, commercial growers or local governments for use as fertilizers or soil conditioners for food- and non-food-chain vegetation. Usually in this category, the sludge has undergone some dewatering treatment to reduce the volume of sludge before distribution. In addition, humus material or nutrient additives may have been blended with the sludge to increase its fertilizer or soil conditioning value and to give it a more acceptable texture. The sludge may also have been composted to reduce its biochemical oxygen demand, odor and pathogen load.

Risk assessment for pathogens in municipal sludges requires the following input data:

- Survival capability, numbers (level or concentrations) and types of pathogens present in the sludge, along with a consideration of their virulence or infective dose (minimal infective dose or MID);
- The sludge reuse/disposal option used and the conditions of sludge application (quantities, frequencies, application method, etc.); and
- The fate of the pathogens in the environment, including the magnitude, duration and routes of exposure from the applied sludge to human receptors.

Considering modern disposal practices, almost any pathogenic organism can be found in municipal sewage. The following section characterizes the pathogens of concern in sewage sludges.

2.3.1. Hazard Identification. Hazard identification normally consists of identifying the critical effect, which is the adverse effect occurring at the lowest dose. In the case of pathogen risk assessment, the hazard identified is any adverse consequence to human health resulting from exposure to pathogenic microorganisms. The microbial composition of sewage wastes is variable and heterogeneous. Therefore, a quantitative hazard identification for microbial pathogens may be difficult to achieve because it involves an aggregate of hazard assessments for each of a generally unknown number of species of pathogenic organisms, often present in poorly characterized concentrations.

The presence of pathogens in municipal sludge is well documented. Several reviews include surveys of pathogens present in sludge at different stages of treatment, and most comment on the relative pathogenesis of these populations (WHO, 1981; Kowal, 1982, 1985; U.S. EPA, 1986). Table 2-1 presents the pathogens most commonly found in sewage sludge and the diseases caused by them.

For purposes of discussion, sewage-borne pathogens are generally divided into four or five major groups: bacteria, viruses, protozoa, helminths and, sometimes, fungi. Fungi are generally not significant pathogens in sewage except in relation to composting

TABLE 2-1

Pathogens of Primary Concern in Sewage Sludges*

Type	Organism	Effect
Bacteria	*Campylobacter jejuni*	gastroenteritis
	Escherichia coli (pathogenic strains)	gastroenteritis
	Leptospira spp.	Weil's disease
	Salmonella spp.	gastroenteritis, enteric fever
	Shigella spp.	gastroenteritis
	Vibrio cholerae	cholera
	Yersinia enterocolitica	gastroenteritis
Viruses	Adenovirus	respiratory disease, eye infections, gastroenteritis
	Astrovirus	gastroenteritis
	Calicivirus	gastroenteritis
	Coronavirus	respiratory infections
	Enteroviruses	gastroenteritis, meningitis,
	Coxsackievirus A	meningitis, herpangina, fever, respiratory disease
	Coxsackievirus B	myocarditis, congenital heart anomalies, pleurodynia, respiratory disease, fever, rash, meningitis
	Echovirus	meningitis, diarrhea, rash, fever, respiratory disease
	Hepatitis A virus	infectious hepatitis
	Numbered enteroviruses	conjunctivitis
	Poliovirus	meningitis, paralysis, fever
	Epidemic non-A non-B hepatitis	hepatitis
	Norwalk viruses	gastroenteritis
	Pararotavirus	gastroenteritis
	Parvovirus	aplastic crisis, erythema, fetal death, hydrops fetalis
	Reovirus	not clearly established
	Rotavirus	diarrhea, vomiting
	Snow Mountain Agent	gastroenteritis
Protozoans	*Balantidium coli*	balantidiasis
	Cryptosporidium sp.	gastroenteritis
	Entamoeba histolytica	amebic dysentery
	Giardia lamblia	giardiasis
	Toxoplasma gondii	toxoplasmosis

TABLE 2-1 (cont.)

Type	Organism	Effect
Helminths	*Ancylostoma duodenale*	hookworm
	Ascaris lumbricoides	ascariasis
	Hymenolepis nana	taeniasis
	Necator americanus	hookworm
	Strongyloides stercoralis	abdominal pain, nausea, diarrhea
	Taenia sp.	taeniasis
	Toxocara spp.	visceral larva migrans
	Trichuris sp.	whipworm
Fungi	*Aspergillus fumigatus*	aspergillosis or respiratory infections
	Candida albicans	candidiasis
	Cryptococcus neoformans	subacute chronic meningitis
	Epidermophyton spp. and *Trichophyton* spp.	ringworm and athlete's foot
	Trichosporon spp.	infection of hair follicles
	Phialophora spp.	deep tissue infections

* Source: U.S. EPA, 1985a; Gerba, 1983; Thurn, 1988; Hurst, 1989.

of sludge, as discussed below. Most pathogenic microorganisms found in sewage cause gastroenteric disease of some form, although secondary effects of the organisms may also be important.

2.3.1.1. Pathogenic Bacteria -- Escherichia coli and Campylobacter are significant causative agents of waterborne gastroenteritis throughout the world. Mortality is generally low except in persons with low natural resistance to infection.

Leptospira is found in the urine of infected animals. It can cause a variety of usually mild symptoms. Its spread is usually limited to contact with infected urine.

Salmonella is a major causative agent of food poisoning and typhoid fever. It can contaminate vegetable, meat and dairy products produced on sludge-amended land. The organism is readily transferred from contaminated to uncontaminated foodstuffs by direct contact or via the hands of persons preparing the food. Spread of sludge-borne Salmonella can effectively be curbed by good sanitary practices during food preparation (WHO, 1981). The relative importance of sludge as a source of Salmonella infection may be small compared to other sources, such as highly mechanized food preparation methods in which insufficient care is given to sanitation. A report by the World Health Organization points out that the worldwide incidence of disease caused by Salmonella has risen (WHO, 1981), as has the incidence in the United States (U.S. PHS, 1985), while agricultural use of untreated sewage and sludge has fallen.

Shigella causes bacillary dysentery, a disease characterized by severe discomfort but usually low mortality rates. The disease is spread very easily by the fecal-oral route under conditions of poor sanitation. Therefore, a single case of sludge-borne infection may give rise to many cases of disease in the population.

Vibrio cholerae is the causative agent of cholera, which has a high mortality rate if not treated, but a low mortality rate if appropriate supportive measures are taken.

Yersinia enterocolitica causes a gastroenteritis with low mortality rates. The disease appears only sporadically in the United States.

2.3.1.2. Viruses -- Adenoviruses are infectious by inhalation or by ingestion. Ingested adenovirus causes a mild gastroenteritis, but aerosol infections can cause serious respiratory disease or blindness.

Enteroviruses cause relatively mild gastrointestinal symptoms, but they may also invade the circulatory system and attack the nervous system or other major organs. Poliomyelitis is a well-known, but now rare, complication of infection with poliovirus, while viral meningitis is not uncommon. Hepatitis A virus attacks the liver, but permanent damage is rare.

Diseases caused by the other viruses listed in Table 2-1 are less significant, most only causing mild gastroenteritis. As techniques for detecting and isolating viruses become more sophisticated, more viruses are found in sewage and sludge. The medical significance of these recently-found viruses is still being determined.

2.3.1.3. Protozoans -- The protozoan pathogens cause a variety of symptoms by colonizing the gastrointestinal tract. Protozoan diseases may be debilitating but are rarely fatal in developed countries. Protozoa are present in sewage and sludge as cysts, dormant structures resistant to adverse environmental conditions.

2.3.1.4. Helminths -- The pathogenic helminths include a variety of worms, some of which are only incidental parasites of humans. Among them are pinworms, roundworms, whipworms, and a variety of tapeworms. The larval stages of helminths often migrate through the body before maturing in the gut and can cause serious tissue and organ damage. Adult forms primarily cause malnutrition and anemia while residing in the gut. Helminths are present in sewage and sludge as ova.

2.3.1.5. Fungi -- Fungi are predominantly opportunistic pathogens in sewage. Infection with fungi associated with sludge is generally by aerosol or direct contact routes. Fungal infections are uncommon in healthy individuals, so that infections are often associated with low resistance or compromised immunity and are likely to be persistent.

As a part of EPA's efforts to evaluate the feasibility of pathogen risk assessment for sludge, more comprehensive data on pathogenic organisms are discussed in Pathogen Risk Assessment Feasibility Study (U.S. EPA, 1985a) and Development of a Qualitative Pathogen Risk Assessment Methodology for Municipal Sludge Landfilling (U.S. EPA, 1986).

Although performing risk assessments for all, or at least most, of the pathogens present in sewage sludge would be ideal, designing a model that could accurately simulate the survival and environmental movement of more than a few specific organisms would be difficult. Therefore, organisms or organism groups were selected to represent the enteric pathogens most commonly found in sludge. The following criteria have been used to select these representative pathogens:

1. The pathogen is known to be present in municipal sludge.
2. The pathogen is known to cause human disease.
3. More data are available for the representative pathogen than for others in the same microbial group.
4. Its survivability is typical of other members of the group.

5. Minimum infective doses (MIDs) are known.
6. The pathogen survives outside the human host.
7. The infective routes--ingestion, inhalation, or skin contact--are known.

The pathogenic organisms initially selected by the EPA as representative of pathogens present in municipal sludges were:

1. Salmonella spp., as an example of pathogenic enteric bacteria;
2. Enteroviruses, as an example of enteric viruses;
3. Entamoeba histolytica and Giardia lamblia, as examples of parasitic protozoans;
4. Ascaris lumbricoides and A. lumbricoides var. suum, as examples of helminths; and
5. Aspergillus fumigatus, as a representative of pathogenic fungi.

The current version of the model deals with only three of the representative pathogens--Salmonella spp. representing the bacteria; Ascaris lumbricoides, the parasites (both helminth worms and protozoa); and enteroviruses (a grouping of several animal viruses), the enteric viruses. No representative for the fungi was selected because the available information concerning this group is inadequate to support a quantitative assessment. Moreover, the scientific literature provides little documentation of fungal disease as a consequence of exposure to wastewater or sludge.

The selection and use in risk determination of representative pathogens does not preclude the performance of risk assessments with other pathogens of particular importance, such as infectious hepatitis virus.

2.3.2. Dose-Response Assessment. Consequences of exposure to a pathogen are variable. The organism may (1) not penetrate host defenses; (2) initiate a transitory colonization which is self-limiting or eradicated by host defenses such as inflammation or the immune response; (3) establish a long-term infection without overt symptoms; (4) cause mild or acute disease; or (5) kill the host. These responses depend, to some extent, on properties of both the pathogen and the host and, usually, on the number of infecting microbial cells present. Thus, there is no clearly defined exposure that will always lead to infection, even with only a single microbial species or strain. An understanding of the dose-response relationship for each pathogen is important in estimating the risk associated with the presence of the pathogen in sludge.

The dose-response assessment characterizes the relation between exposure to pathogens and occurrence of adverse health effects. This relationship is based on the number of viable organisms ingested and the dose of the organism required to cause infection in a susceptible host. Exposure levels calculated by the model and assumed or experimentally derived values for infectious dose are used to assess the risk of infection.

Exposure of an individual to enteric pathogens can lead to (1) no effect, (2) a subclinical (asymptomatic) infection or (3) a clinical (symptomatic) infection. Although subclinical infections produce no symptoms in the infected host, that individual, by either direct or indirect transmission of the pathogenic organisms, may cause disease to develop in others. In this methodology, infection rather than disease will be used to measure risk.

This methodology assumes that exposure to enteric pathogens will not result in infection unless the organisms are actually swallowed. Most exposures, therefore, should result from consumption of contaminated foods or liquids. Risks due to inhalation of enteric pathogens will be considered only because the organisms can be subsequently swallowed. Disease could result through routes of exposure other than the alimentary tract, and initial propagation of enteric organisms could occur at a site different from the intestine of the infected individual. Such mechanisms of infection and propagation are uncommon for enteric pathogens, however, and will not be considered for purposes of risk assessment.

The dose required to cause infection is based on the virulence or infectivity of the pathogenic organism and on the susceptibility of the exposed population or individual receptor. Virulence, or degree of pathogenicity of an organism, is a somewhat quantitative reflection of the ability of the organism to establish infection and may depend on the organism's ability to overcome host defenses. The virulence of a given organism can vary, depending on its recent history. In addition, the medium in which the dose is administered can also affect the observed response. Similarly, resistance mechanisms (including barriers to infection, inflammatory responses, and specific immune responses) vary among individual hosts. Humans vary in their susceptibility to pathogens, depending on route of exposure, age of the exposed individual, quality of normal bodily defense systems, existing microbial populations in the host, and other poorly defined properties. The differences in susceptibility of the host population are usually reflected in the consequences of infection. Thus, experimental exposure of an immunologically experienced population may elicit a secondary immune response but little infection, whereas a previously unexposed population may exhibit a higher incidence of infection and disease.

The "minimum infective dose" or MID is typically the dose required to infect 50% of the population. Estimates of the number of microorganisms required to produce infection can be made either by exposing volunteers to known doses of the pathogen or by inferring from epidemiological data the probable levels of exposure that are associated with observed frequencies of infection or disease.

When virus concentrations are determined by infecting an indicator cell line, the information gained is a ratio of infective activities. The most quantitative determination, the plaque assay, yields a concentration of infective virus units; but the dose producing the plaque formation response must also be known because, in some instances, more than one infectious virus particle may be required to initiate plaque formation. When infection can only be measured by cytopathic effect, it may be necessary to calculate a Tissue Culture Infective Dose (usually $TCID_{50}$, i.e., dose required to infect 50% of the cultures). In this case, also, the dose-response relationship of the indicator cell line to infection must be known for an accurate calculation of the dose-response effect in humans.

The reported infectious doses may vary widely for a given pathogen. For example, the reported MID for Salmonella varies from 10^2 to 10^8 organisms (Blaser and Newman, 1982; Kowal, 1982, 1985) and for poliovirus from 1 $TCID_{50}$ to around 4×10^5 $TCID_{50}$ (Kowal, 1982). The uncertainty in measuring infectious doses greatly weakens the power of any quantitative risk assessment. The model is designed, therefore, so that the user can supply a best estimate of infectious dose for the particular pathogen and practice being modeled. The following MIDs are used as default values in the model: Salmonella, MID=10; Ascaris lumbricoides, MID=1; and enteroviruses, MID=1.

2.3.3. Exposure Assessment. The exposure assessment step begins with the identification of pathways of potential exposure, that is, migration routes of pathogens within or from the application or disposal site to a target organism or receptor. Pathogens leached into surface water can be transported as runoff into rivers, lakes or oceans. They may also become associated with particulate materials in the runoff water and be deposited as sediments along the route of transport. Contaminated soil may become airborne as a result of wind erosion or mechanical disturbance and, thus, may be inhaled or deposited on crop surfaces. Contaminated irrigation water or liquid sludge may form aerosols, which can be carried offsite by the wind.

An important factor in the significance of these exposure pathways is the survival time of pathogens, most of which are poorly adapted to survive in soil. Microorganisms are inactivated in soil at rates that vary with the type of organism, the degree of predation by other microorganisms, the amount of sunlight, and the physical and chemical composition of the soil, including moisture content, pH and temperature (Gerba et al., 1975; Kowal, 1985). Bacteria and viruses survive well at neutral or slightly alkaline pH, whereas acid soils reduce survival times. Moist, cold soils contribute to increased survival time of bacteria, viruses, protozoan cysts and helminth ova; and, therefore, soils with a higher percentage of organic matter that have a greater water-holding capacity may be more conducive to pathogen survival. Virus survival time in soil decreases with dessication and higher temperatures, and protozoan cysts are also extremely sensitive to drying. Likewise, helminth eggs and larvae are susceptible to die-off when exposed to desiccation and sunlight, but in cool, moist soil they may remain infective for several years (Kowal, 1985). Soil protozoa prey on bacteria; competition and antagonism from endemic soil microorganisms decrease bacteria survival time, although soil microorganisms seem to have less of an effect on virus degradation (Kowal, 1985).

Following surface application, the transport of pathogens through unsaturated soil is influenced by the porosity, ionic composition and pH of the soil. Bacteria are readily retained by filtration in soil. Most bacteria do not migrate more than about 50 cm in soil, although extensive migration can be observed in gravelly or fissured soil (U.S. EPA, 1986; Kowal, 1985). Viruses are not as readily filtered from the percolating water because of their small size and can be found in groundwater after application of effluent to sandy soil (Goyal et al., 1984; Wellings et al., 1975). However, they do adsorb to soil organic matter and clay particles (Wang et al., 1985; U.S. EPA, 1986). The extent of adsorption of bacteria and viruses depends on the ionic strength of the soil pore water and the ionic composition of the soil. Adsorbed microorganisms can be washed free by water of low ionic strength, so that a heavy rain may result in an increase in the number of virus particles and bacteria being released into groundwater. Experimental studies have shown, however, that if virus suspensions in soil columns are allowed to drain dry, live viruses are not readily eluted by addition of water (Lance & Gerba, 1980). Therefore, it is likely that inactivation of virus particles occurs upon drying, despite the protective properties of soil. Protozoan cysts and helminth ova are large enough that they exhibit very little migration through soil.

Bacteria and viruses have been observed to move readily through saturated soils (Lance and Gerba, 1984), indicating that rapid transport of pathogens in an aquifer is probable. As a result, care must be taken in choosing sites for land disposal of sludge and wastewater so as to avoid infiltration of pathogens into any aquifer.

In this pathogen risk assessment methodology, humans are the receptors of concern. The available risk assessment models for microbial pathogens are variable and limited in their treatment of exposure pathways. Such pathways to humans for land application of sludge and wastewater can include the following:

- Ingestion of soil or sludge;
- Inhalation of aerosols;
- Leaching of pathogens from land application sites to surface water and groundwater, and subsequent ingestion;
- Transfer of pathogens to vegetation or food crops and subsequent ingestion;
- Transfer from soil, water or vegetation to animals by contact or ingestion and subsequently, transfer to humans.

Since the model provides only an approximation of environmental transport mechanisms, it does not represent every possible exposure pathway. It does, however, trace the flow of pathogens through the major routes leading to possible human exposure.

The following human receptors are the exposed individuals whose probability of infection by microbial pathogens is calculated by this model:

- Onsite person who is exposed by direct contact with soil, vegetables, or forage or by inhalation and subsequent ingestion of aerosols (particulates or liquid);
- Offsite person who is exposed to particulate or liquid aerosols carried by wind;
- Food consumer who eats vegetable crops, meat or milk produced on sludge-amended soil;
- Groundwater drinker who consumes water from a well near the sludge application site;
- Pond swimmer who ingests a small amount of water while swimming in the pond that receives the surface runoff from the application site.

In assessing human exposure, it would be preferable to define the full spectrum of potential levels of exposure and the number of individuals at each level, thus quantifying the exposure distribution profile for a given exposure pathway. Such a task exceeds the scope of the present effort; however, by varying the values of the parameters that determine exposure, the user may gain an appreciation for the range of potential risks faced by exposed individuals. A list of default values defining reasonable worst-case assumptions is provided for use in testing the model. However, the compounding of worst-case assumptions can lead to improbable results. Therefore, the key to effective use of this methodology will be a careful and systematic examination of the effects of varying each of the input parameters, using estimates of central tendency and upper-limit and lower-limit values to gain an appreciation for the variability of the result. An approach to this is provided in Chapter 7, Sensitivity Analysis.

Exposure, for purposes of this methodology, will be determined for a conservatively defined human receptor.[1] The definition of the human receptor will vary with each human exposure pathway. Chapter 4 enumerates the exposure pathways and defines the human receptor in qualitative terms; e.g., for the home garden scenario, the human receptor is a person producing much of his or her own crops on sludge-amended soil. The human receptor is not defined quantitatively in Chapter 4, but relevant information that allows the user to do so (such as available data on the ranges of crop consumption rates) is provided in Volume II: User's Manual.

2.3.4. Risk Characterization. Risk characterization consists of combining the exposure and dose-response assessment procedures to estimate the incidence of a health effect. Risk assessment analysis ordinarily proceeds from source to receptor. That is, the source, or sludge disposal/reuse practice, is first characterized, and contaminant movement away from the source is then modeled to estimate the degree of exposure to the human receptor. Human health effects are then predicted based on the estimated exposure and dose-response relationships. This computer model sums the exposures of a human receptor to pathogens every hour and computes the daily probability of the human receptor receiving an exposure exceeding an infective dose (for Salmonella, the MID=10). Each exposure compartment adds a current value every hour to the accumulated exposure, resulting in a total daily (24-hour) exposure that is used in the calculation of risk to the described human receptor for the exposure compartments in that practice.

2.4. POTENTIAL USES OF THE METHODOLOGY IN DETERMINING RESEARCH NEEDS

One of the values of the pathogen risk assessment methodology and computer model described herein is its ability to identify areas in which additional research is needed. For example, a major hurdle in any risk assessment is estimating exposure by a variety of routes or pathways to a population that varies according to activity patterns. The use of a conservatively defined human receptor is based, at least in part, on the difficulty in estimating exposure of a population to a changing level, or dose, of pathogens. Information on infectious dose for most pathogens is limited, and distribution of pathogens in soil or groundwater is poorly understood. This model assumes random distribution of pathogens in environmental media, a commonly-made assumption, but probably frequently violated. Further research on pathogen exposure pathways and infectious dose levels would facilitate the predictive accuracy of this model and its successors.

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[1] The definition of the human receptor does not include workers exposed in the production, treatment, handling or transportation of sludge. This methodology is geared toward protection of the general public. It is assumed that workers can be required to use special procedures or equipment to minimize their exposure to sludge-borne contaminants. Agricultural workers, however, might best be considered members of the general public since the use of sludge may not be integral to their occupation.

Another obvious data gap, illustrated by this methodology and model development, is the degree of survival and transport of pathogens in the environment. Information on the fate of pathogens in groundwater and subsurface soil is extremely limited. The concentration and survival rates of pathogens leaching through soil into groundwater are unavailable for viruses, protozoa, and helminths, while bacterial concentration data are few (U.S. EPA, 1986). More data are needed concerning the transport of pathogens through the unsaturated zone, especially with respect to rainfall effects.

In conjunction with the results of the sensitivity analysis, this model should be laboratory- and field-validated, thereby revealing other research needs.

2.5. LIMITATIONS OF THE METHODOLOGY

Limitations of the calculation methods for each pathway are given in Chapter 5, along with examples of calculation methods. However, certain limitations common to any model, including the calculation methods, are stated in this section. In several cases, simplifying assumptions have been made to prevent the model from becoming too cumbersome for practical application. If the user were required to input all possible variables, the time required to collect the information and to enter it prior to a model run would be prohibitive. As a result, the flexibility of the model has been restricted to some extent.

The predictive value of the model depends on reliable input parameters and on the accuracy with which initial pathogen concentrations are determined. Municipal sludges are highly variable mixtures of residuals and by-products of the wastewater treatment process, and the distribution of microbial types in sludge will depend, to some extent, on the effects of sewage constituents on competition among and between microbes. Also, variations in sewage may result in varying efficacy of treatment, so that the concentration of a particular pathogen cannot be precisely predicted. Variability in weather or farming practices is likely to result in differing rates of growth or die-off in soil, air and water. Exponential growth and die-off rates are assumed to apply until the end of the practice, even though under certain circumstances linear growth or die-off rates may be more appropriate; consequently, the modeled rates may not be completely realistic.

Times of transfer from compartment (see Section 3.2 for a description of transfers and compartments) to compartment are, in some cases, arbitrary, rather than being functions of processes in the source compartment, and default times may not be realistic. Timing of irrigation and rainfall are specified by the user, but with very limited options. Although an irrigation schedule may be established by the farmer, good agricultural practice will allow the schedule to vary according to the effects of temperature, wind and rainfall on immediate soil conditions. This degree of flexibility has not been built into the model.

Algorithms for generation of particulate clouds due to tilling or wind are necessarily oversimplified. For the purposes of this model, too many factors are required to describe accurately the types of farm equipment used, the conditions of soil moisture, ground cover, variations in wind speed and direction, size and location of fields, and location of the human receptor. The model is based on approximations or stipulated default values of these parameters. Similarly, for offsite exposure to airborne pathogens, variations in wind direction and speed are not considered. In the default condition, concentrations are calculated only for a line directly downwind from the source. Concentrations at a specified distance from the center of the plume can be calculated, but the entire plume is not described in a single run of the model.

The algorithm used for movement of pathogens by surface runoff and sediment transport has been shown to be adequate for describing these processes for water and soil, but it has not been validated for microbial transport. It is, at best, only an approximation of reality, and it is accurate only to the extent that each of many variables is a good description of actual conditions at the study site. The model assumes that surface runoff is collected in an onsite pond. No allowance is made for variations in terrain or soil type in the area being modeled.

Transport of pathogens through the aquifer to an offsite well is modeled by an adaptation of an algorithm for transport of chemicals. The model is limited primarily by uncertainties in the appropriate values to be used for dispersion coefficient and retardation factor, but it is also constrained to a receptor directly downflow from the source in the center of the contaminant plume. It assumes instantaneous mixing of pathogens with the groundwater upon their input into the compartment, and it is intended to describe only transport in a straight line from a point source to the receptor well. It also assumes homogeneity of the aquifer medium, with no cracks or solution channels. These assumptions are almost certainly not entirely correct for any site. In addition, the model makes no distinction between confined and unconfined aquifers; instead, it calculates transport strictly on the basis of distance. For example, a well drilled to a depth of 75 m into a confined aquifer 100 m from the source will be treated the same as a shallow well in an unconfined aquifer at a distance of 125 m from the source, even though a confined aquifer may have no contact with overlying groundwater.

Simplifying assumptions have been made in the descriptions of farming, gardening and home use practices, and processing of crops for consumption or sale. The default irrigation option is spray irrigation because the model assumes that generation of aerosols by spray irrigators will provide a worst-case situation.

The model also assumes that the probability of infection is adequately described by the Poisson distribution; however, there is no precise exposure value below which infection will not occur and above which it will always occur. Exposures are treated as acute exposures accumulated over one day, with no consideration for effects of chronic exposures. In addition, the methodology compartmentalizes risks according to separate exposure pathways.

3. SLUDGE MANAGEMENT PRACTICES

3.1. INTRODUCTION

Sludge is a mixture of solids and liquid resulting from some process that causes or allows settling of particulate material from suspension. Sludges can be generated by a number of industrial processes, and many of them are classified as hazardous wastes (Sittig, 1979). Chemical sludges are generally too toxic to support the growth of microorganisms. Sewage and its associated sludge, in contrast, are rich in organic nutrients, are low in toxic chemicals and have a reasonable pH range. Consequently, they readily support microbial growth. Indeed, because bacterial decomposition of organic materials constitutes a major part of sewage treatment, it is essential that sewage support bacterial growth. This discussion, therefore, is limited to sludge generated by treatment of municipal or household sewage.

Sludge is a byproduct of sewage treatment. Domestic and municipal wastes include solids, and during the treatment process, dissolved organic and inorganic materials are converted to solids. A Federal requirement for secondary treatment of all sewage (Clean Water Act, P.L. 92-500 and amendments) has ensured that the quality of wastewater discharged from treatment facilities is high, but, as a result, the amount of sludge generated has increased. The per capita production of sewage was estimated over a decade ago to be around 100 gal/day (400 L/day) for a residential population and more than 300 gal/day (1200 L/day) in a more highly industrial area (James, 1976). Total municipal sludge production was estimated in 1982 at more than 6.8 million metric tons dry weight (DW), with an anticipated two-fold increase by the year 2000. A survey of 6.5% of the U.S. treatment plants in 1982 revealed that land application and distribution and marketing (D&M) practices accounted for 2.87 million tons DW, or 42% of total sludge production (U.S. EPA, 1983b). The use of landfills for sludge disposal is limited both by the availability of vacant land and by objections of the public to having sludge disposal sites located near their homes. Therefore, other disposal alternatives are necessary. U.S. EPA guidelines encourage municipalities to consider land application of sludge whenever feasible.

Because municipal sewage contains human sanitary waste, microorganisms that colonize humans will be present in sewage. Among these microorganisms will be some that cause disease. Therefore, assessing the efficacy of treatment processes in reducing the concentrations of pathogenic microorganisms and, subsequently, assessing the risk to human health posed by those pathogens are essential if sludge disposal might lead to subsequent human contact.

There are few quantitative methodologies available at this time for assessing risk to human populations from sludge disposal practices. Responses of different pathogens to treatment conditions, interactions of pathogen types with environmental conditions and responses of human populations to pathogens over different exposure routes are complex. Information in these areas is incomplete and often inconsistent, leading to a great deal of uncertainty about quantitation.

Extensive background information relevant to the conceptual risk assessment framework for land application of sewage sludge has been provided by the U.S. EPA (1986). This key study addresses the pathogens associated with sewage sludge, as well as exposure pathways and the potential risks to humans from each of the pathways. Most of that information will, therefore, not be repeated here. The following discussion briefly defines the practices included within the land application and D&M management options.

3.2. MODEL OVERVIEW

A total of five sludge management practices, listed in Table 3-1 and illustrated in Figures 3-1, 3-2, 3-3, 3-4 and 3-5, are included in the present model. Two of the practices use heat-dried or composted sludge for residential purposes, and three use liquid sludge for a group of commercial farming operations. Since each of these two types of sludge represents a wide range of sludge treatment possibilities, the extent of treatment or conditioning prior to land application must be approximated for each case (i.e., the pathogen concentration in the applied sludge must be specified). The computer model represents the compartments and transfers among compartments of the five management practices. The compartments are the various locations, states or activities in which sludge or sludge-associated pathogens exist; they vary to some extent among practices. Compartments that represent sources of human exposure are designated with an asterisk in the flow diagrams for each practice. In each compartment, pathogens either increase, decrease or remain the same in number with time, as specified by "process functions" (growth, die-off or no population changes) and "transfer functions" (movement between compartments). Process functions are designated by RHOx, and the transfer functions are designated as TRxy where x is the compartment from which pathogens are being transferred and y is the compartment to which they are being transferred. For example, a transfer from Compartment 1 to Compartment 2 would be TR12. The population in each compartment, therefore,

TABLE 3-1

Sludge Management Practices and Descriptions

Practice	Description*
I	Application of Liquid Sludge for Production of Commercial Crops for Human Consumption
II	Application of Liquid Sludge to Grazed Pastures
III	Application of Liquid Sludge for Production of Crops Processed before Animal Consumption
IV	Application of Dried or Composted Sludge to Residential Vegetable Gardens
V	Application of Dried or Composted Sludge to Residential Lawns

*Two types of sludge are used in this model - liquid and dried/composted. The extent of treatment or conditioning prior to application is variable and must be determined for each case.

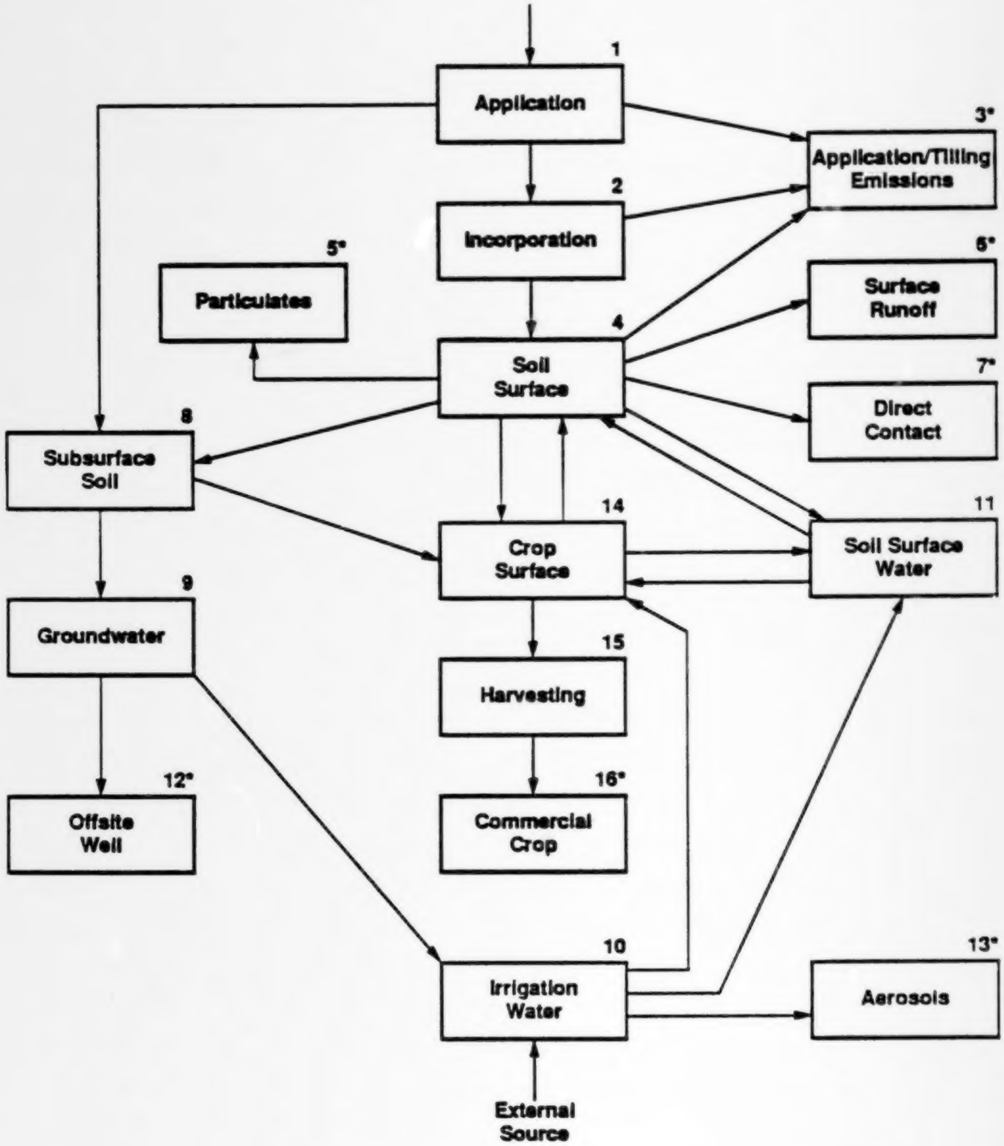
1
Application
3*
Application/Tilling Emissions
2
Incorporation
5*
Particulates
6*
Surface Runoff
4
Soil Surface
7*
Direct Contact
8
Subsurface Soil
14
Crop Surface
11
Soil Surface Water
9
Groundwater
15
Harvesting
12*
Offsite Well
16*
Commercial Crop
10
Irrigation Water
13*
Aerosols
External Source

FIGURE 3-1

Input/Output Diagram for Practice I – Application of Liquid Sludge for Production of Commercial Crops for Human Consumption

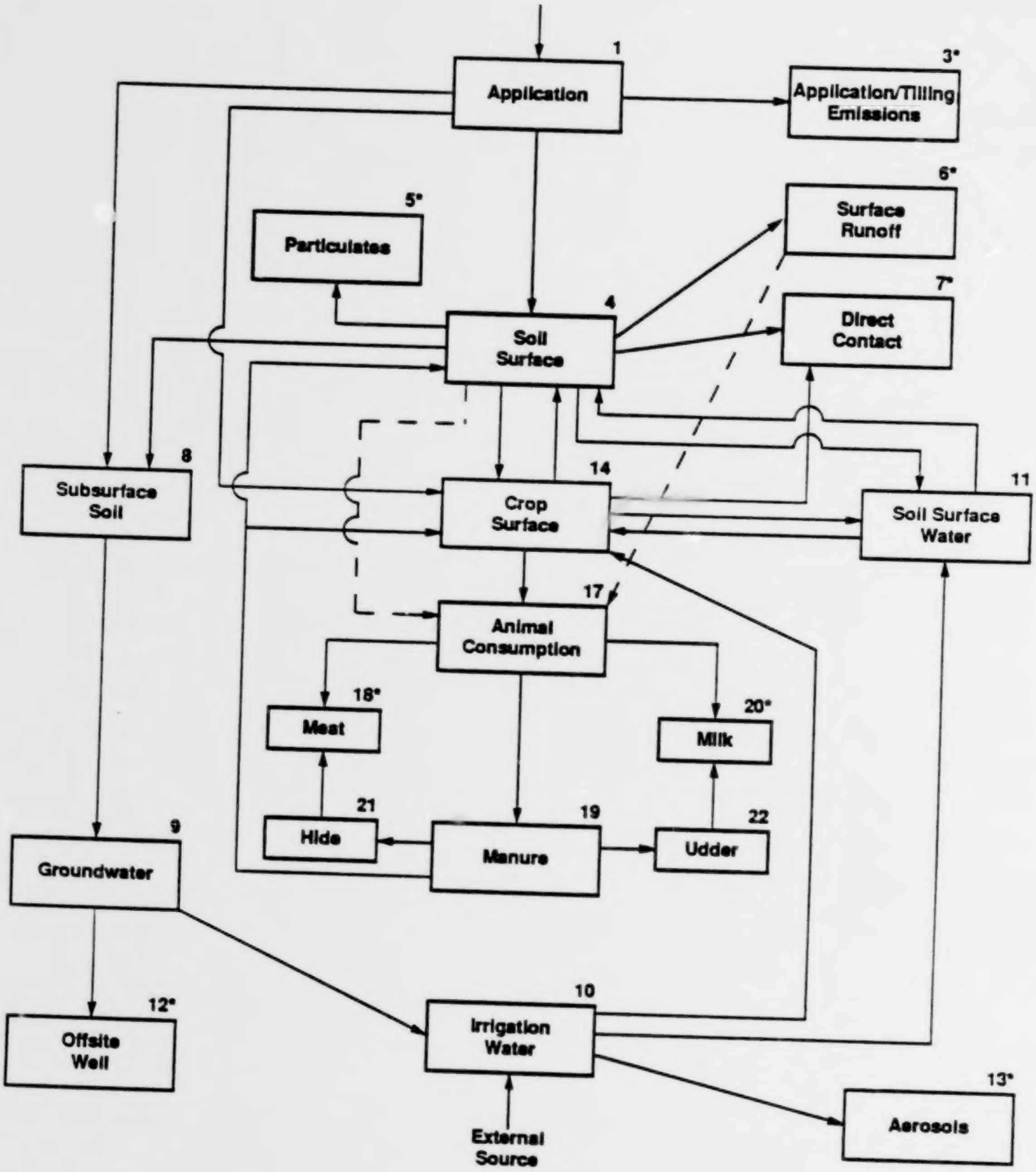
1
Application
3*
Application/Tilling Emissions
6*
Surface Runoff
5*
Particulates
4
Soil Surface
7*
Direct Contact
8
Subsurface Soil
14
Crop Surface
11
Soil Surface Water
17
Animal Consumption
18*
Meat
20*
Milk
21
Hide
19
Manure
22
Udder
9
Groundwater
10
Irrigation Water
12*
Offsite Well
13*
Aerosols
External Source

FIGURE 3-2

Input/Output Diagram for Practice II – Application of Liquid Sludge to Grazed Pastures

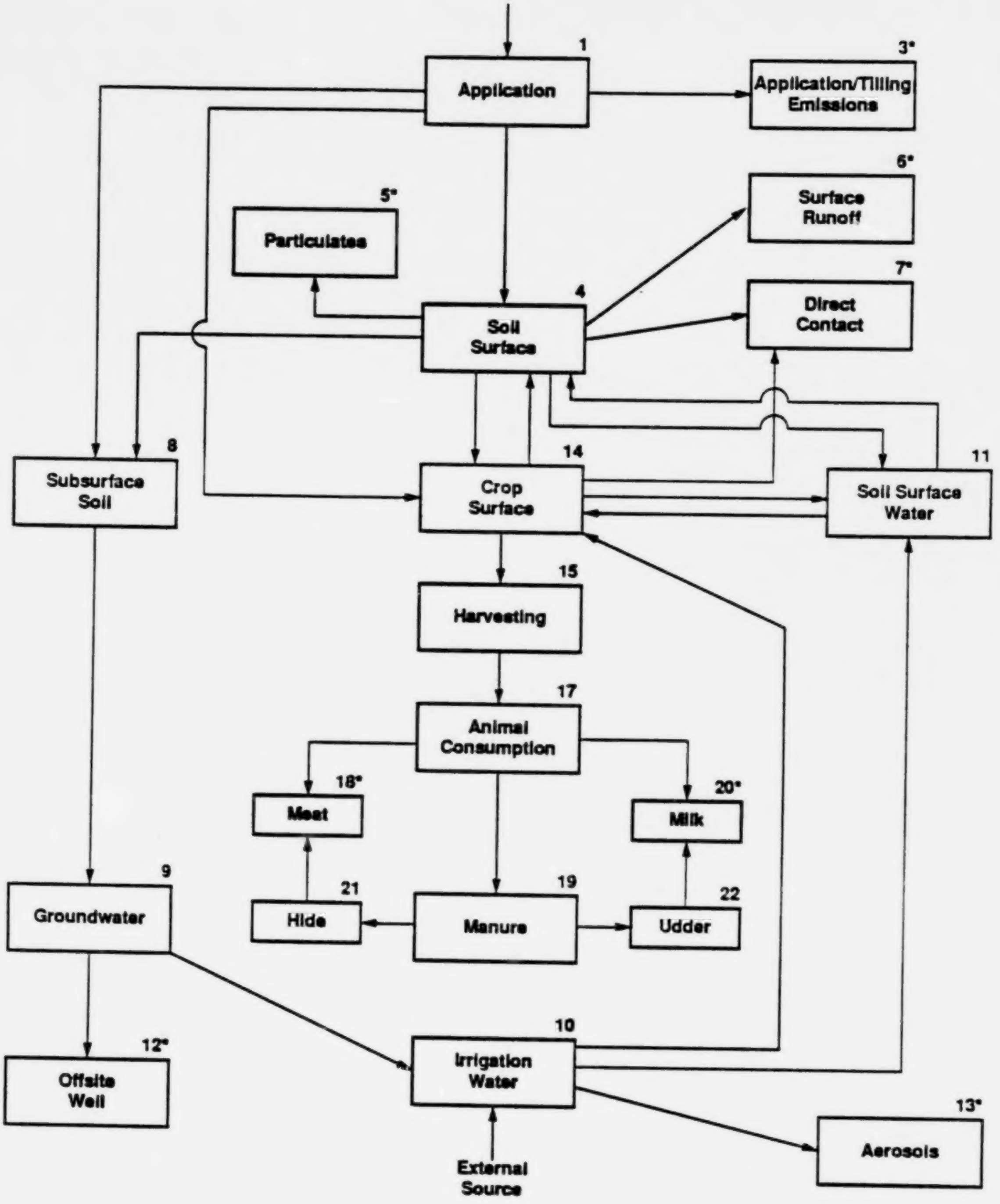
1
Application
3*
Application/Tilling Emissions
6*
Surface Runoff
5*
Particulates
4
Soil Surface
7*
Direct Contact
8
Subsurface Soil
14
Crop Surface
11
Soil Surface Water
15
Harvesting
17
Animal Consumption
18*
Meat
20*
Milk
9
Groundwater
21
Hide
19
Manure
22
Udder
10
Irrigation Water
12*
Offsite Well
13*
Aerosols
External Source

FIGURE 3-3

Input/Output Diagram for Practice III – Application of Liquid Sludge for Production of Crops Processed before Animal Consumption

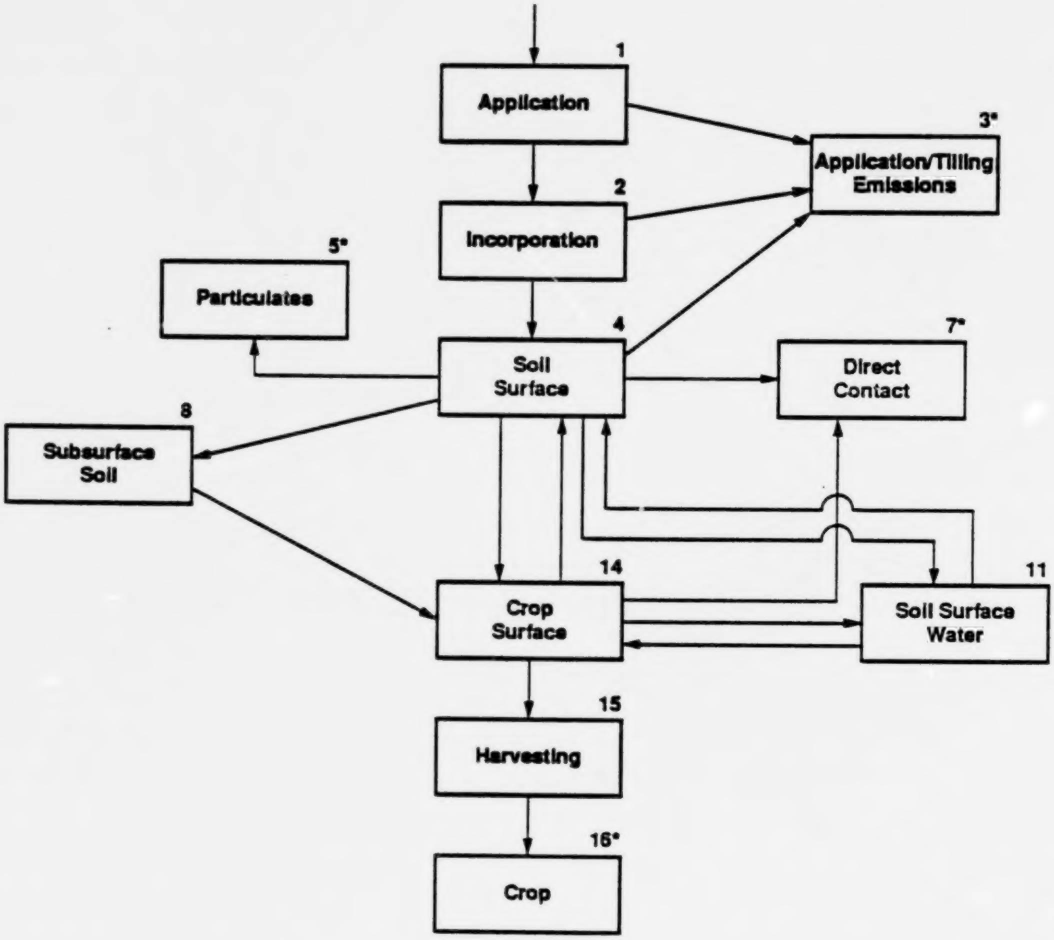
1
Application
3*
Application/Tilling Emissions
2
Incorporation
5*
Particulates
4
Soil Surface
7*
Direct Contact
8
Subsurface Soil
14
Crop Surface
11
Soil Surface Water
15
Harvesting
16*
Crop

FIGURE 3-4

Input/Output Diagram for Practice IV – Application of Dried or Composted Sludge to Residential Vegetable Gardens

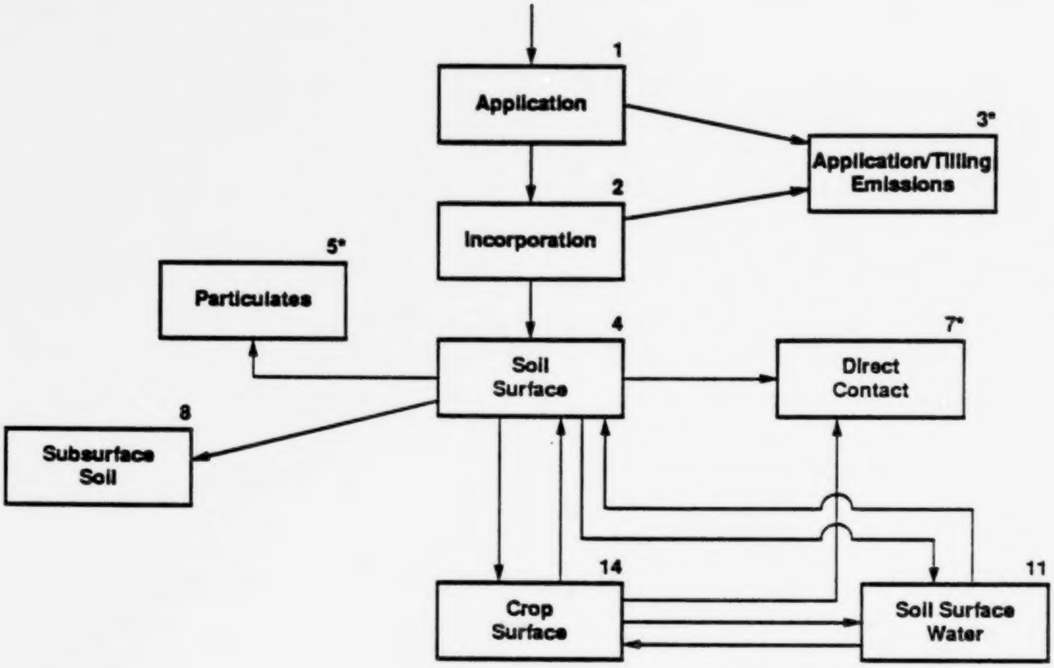
1
Application
3*
Application/Tilling Emissions
2
Incorporation
5*
Particulates
4
Soil Surface
7*
Direct Contact
8
Subsurface Soil
14
Crop Surface
11
Soil Surface Water

FIGURE 3-5

Input/Output Diagram for Practice V – Application of Dried or Composted Sludge to Residential Lawns generally varies with time and is determined by a combination of initial pathogen input, "transfer functions" and "process functions." The populations of pathogens in the compartments representing human exposure locations, together with appropriate intake and infective dose data, are used to estimate human health risk.

Considering modern sanitary disposal practices, any pathogenic organism can be found in municipal sewage. It would be difficult to design a model that could accurately simulate the survival and environmental movement of more than a few specific organisms. For this reason, organisms or organism groups were selected to represent the enteric pathogens most commonly found in sludge (see 2.3.1).

The approach used to develop the sewage sludge pathogen transport model provides a structure capable of supporting both stochastic and deterministic mathematical relationships, i.e., it is a dynamic model that can incorporate site-specific data while allowing process functions to be dependent on environmental factors, such as temperature and rainfall. The model structure provides a flexibility that permits addition or deletion of sludge management practice compartments as well as modifications in process and transfer functions. The model is designed to run on a personal computer with a minimum of 540 KB of free memory.

The modeling effort itself can serve as a tool for identifying areas in which data are currently nonexistent or incomplete and for which further research is needed. Informed judgment estimates were incorporated into the model's treatment of these less-studied areas. As new information becomes available, these estimates can be removed from the model and replaced with supported data. The model can be progressively modified, thus constantly enhancing its predictive accuracy.

Although each practice listed in Table 3-1 is different, all five practices share common characteristics. All compartments that appear in one or more of the five sludge management practices are listed in Table 3-2. The first 14 compartments, most of which are common to all practices, are described below.

APPLICATION (1) represents the application of sludge to a field (default size 10 ha) or to a yard or garden of specified size. The starting time for the simulation (T=0) is when application of sludge begins. Liquid sludge may be applied by spread-flow techniques, by spray, or by subsurface injection. The application rate and pathogen concentrations are variables to be entered by the user of the model. Default values are different for each practice and are given in Appendix A, Table A-1. The position number of each input variable listed in Table A-1 is designated in the text by brackets, e.g., APRATE [P(2)]. APMETH [P(6)], CATTLE [P(78)], CROP [P(66)] and IRMETH

TABLE 3-2

Compartments Included in the Sludge Management Practices

Compartment Name and Number	Liquid Sludge Management Practices I	II	III	Dried/Composted Sludge Management Practices IV	V
Application	1	1	1	1	1
Incorporation	2	2	2		
Application/Tilling Emissions	3*	3*	3*	3*	3*
Soil Surface	4	4	4	4	4
Particulates	5*	5*	5*	5*	5*
Surface Runoff	6*	6*	6*		
Direct Contact	7*	7*	7*	7*	7*
Subsurface Soil	8	8	8	8	8
Groundwater	9	9	9		
Irrigation Water	10	10	10		
Soil Surface Water	11	11	11	11	11
Offsite Well	12*	12*	12*		
Aerosols	13*	13*	13*		
Crop Surface	14	14	14	14	14
Harvesting	15		15	15	
(Commercial) Crop	16*			16*	
Animal Consumption		17	17		
Meat		18*	18*		
Manure		19	19		
Milk		20*	20*		
Hide		21	21		
Udder		22	22		

* Indicates exposure compartment

[P(17)] are used as flags only; TCULT [P(67)], TRAIN [P(13)] and TSLOTR [P(85)] are used as either flags or variables, depending on the values assigned to them.

During spread-flow and spray application, sludge will be spread thinly on the soil, where it will be subject to drying, heating and solar radiation, thus losing the protective benefits provided by bulk sludge. The model assumes, therefore, that inactivation will occur at a rate characteristic of the organism in soil at 5°C above the ambient temperature (Brady, 1974; USDA, 1975) and that liquid sludge is absorbed by the upper 5 cm of soil surface during this time. The default time for transfer from APPLICATION (1) to INCORPORATION (2) is 24 hours, which allows a field treated with liquid sludge to dry sufficiently to plow or cultivate. If the injection option is chosen, the liquid sludge goes directly from APPLICATION (1) to SUBSURFACE SOIL (8).

During spray application of liquid sludge or application of dry composted sludge, droplets or loose particulates may become airborne. Liquid aerosols are modeled by a Gaussian-plume air dispersion model that calculates the downwind concentration of airborne particulates. Dry particulate emissions are calculated using models for generation of dust by tilling or mechanical disturbance of soil. Both are represented as transfers from APPLICATION (1) to APPLICATION/TILLING EMISSIONS (3*).

INCORPORATION (2) involves the mixing, by plowing or cultivation, of the sludge and sludge-associated pathogens evenly throughout the upper 15 cm of soil. Process functions associated with this compartment are the same as for the relevant pathogen type in soil. Particulate emissions generated by cultivation are represented by a transfer from INCORPORATION (2) to APPLICATION/TILLING EMISSIONS (3*) beginning at hour 24, extending for enough time to cultivate the field (at a rate of 5 ha/hour) or till the garden or lawn (at a rate of 0.005 ha/hour). At the end of this time, all remaining pathogens are transferred to SOIL SURFACE (4).

APPLICATION/TILLING EMISSIONS (3*) is an exposure compartment that receives the dust, or suspended particulates, generated by application or by the cultivating or tilling of dried sludge or sludge-soil mixture. It also receives aerosols generated by spray application of liquid sludge. All process functions associated with this compartment are incorporated in the aerosol subroutines (Section 4.6). Onsite emissions are assumed to settle back to the soil surface at the end of the generation period. Exposure in this compartment is by inhalation; but, as in all inhalation exposures, model simplification limits the exposure to the pathogens assumed to be swallowed after the inhaled dust or aerosol spray is trapped in the upper respiratory tract, swept back to the mouth by ciliary action and swallowed.

SOIL SURFACE (4) describes the processes occurring in the upper 15 cm (Practices I, IV and V) or upper 5 cm (Practices II and III) of the soil layer. Microbes are inactivated at rates characteristic for moist soil at 5°C above the chosen ambient temperature. Transfers from SOIL SURFACE occur by wind to WIND-GENERATED PARTICULATES (5*) at a time chosen by the user (TWIND [P(23)]), by surface runoff and sediment transport after rainfall events to SURFACE RUNOFF (6*), by a person walking through the field or contacting soiled implements or clothing or by other casual contact to DIRECT CONTACT (7*), by leaching after irrigation or rainfall to SUBSURFACE SOIL (8), by resuspension during irrigation or rainfall to SOIL SURFACE WATER (11), or at harvest to CROP SURFACE (14).

WIND-GENERATED PARTICULATES (5*) describes the airborne particulates generated by wind. Process functions are the same as for the organism in air-dried soil at the ambient temperature. The exposed individual is standing in the field (onsite) or at a user-specified distance downwind from the field (offsite) during a windstorm. The wind-generated exposure is calculated from user-specified values for duration (DWIND [P(24)]) and severity (WINDSP [P(25)] of the windstorm (default values 6 hours at 18 m/sec (40 mph)).

SURFACE RUNOFF (6*) describes an onsite pond containing pathogens transferred from SOIL SURFACE (4) by surface runoff and sediment transport after rainfall. Inactivation rates in this compartment are characteristic of microbes in water and are much lower than rates for soil. Water is removed from the pond by infiltration and recharge of the groundwater aquifer, but the model assumes that no microbes are transferred by this process. The human receptor is an individual who incidentally ingests 0.1 L of contaminated water while swimming in the pond. This compartment is also an exposure compartment for cattle drinking 20 L of water daily (Practice II).

DIRECT CONTACT (7*) is the exposure compartment for a worker or a child less than 5 years old who plays in or walks through the field, yard or garden, incidentally ingesting 0.1 g of soil or vegetation. This human receptor represents the worst-case example of an individual contacting contaminated soil or soiled clothing or implements. No process functions are associated with this compartment because it is strictly an exposure compartment, and no transfers are made from this compartment because the number of pathogens in it is negligible.

SUBSURFACE SOIL (8) describes the processes and transfers for pathogens in the subsurface soil between 5 (II and III) or 15 (I, IV and V) cm depth and the water table. It also serves as the incorporation site for subsurface injection of liquid sludge.

Process functions in SUBSURFACE SOIL are the same as for moist soil at ambient temperature. The transfer from SOIL SURFACE (4) occurs after each rain or irrigation event as a result of leaching from the soil surface. The time of transfer is calculated by dividing the depth of rainfall or irrigation by the infiltration rate. Transfer to GROUNDWATER is arbitrarily set at one hour later. At present, the relation between unsaturated water flow and subsurface transport has not been well-established. Thus, this model lacks a satisfactory subroutine to describe pathogen transport from the subsurface soil to groundwater. Instead, user-specified constants are used to describe the fraction of pathogens transferred from SOIL SURFACE (4) to SUBSURFACE SOIL (default SUBSOL [P(44)]= 0.0005 for bacteria, 0.001 for enteroviruses and 0 for helminth ova and protozoan cysts) and from SUBSURFACE SOIL (8) to GROUNDWATER (9) (default FRGRND [P(53)]= 0.001 for bacteria and enteroviruses and 0 for helminth ova and protozoan cysts).

GROUNDWATER (9) describes the flow of pathogens in the saturated zone. Process functions are the same as for other water compartments. Transfers occur to IRRIGATION WATER (10) if the groundwater is used for irrigation or to OFFSITE WELL (12*) if used as drinking water. The number of pathogens transferred to IRRIGATION WATER (10) is based on the concentration of pathogens in the groundwater compartment and the total depth of irrigation. The transfer to OFFSITE WELL (12*) is described by a modification of the subsurface solute transfer model of van Genuchten and Alves (1982). Because microbes in suspension are passively transported by bulk water flow and interact with soil particles by adsorption and desorption, they behave similarly enough to dissolved chemicals that existing solute transport models can be used to describe their fate in the saturated zone (Gerba, 1988).

IRRIGATION WATER (10) describes the transfers for pathogen-contaminated water used for irrigation. No processes are associated with this compartment because it is intended as a transition compartment. Irrigation of the field, lawn or garden takes place a user-specified number of times each week (NIRRIG [P(19)]). This irrigation water may come from either an onsite well fed by GROUNDWATER (9) or from an outside source of treated, liquid sludge. The default conditions vary by practice. In either case, AEROSOLS (13*) are generated unless a non-spray option is chosen. Spray irrigation is the default since other methods would not be expected to cause a significant exposure to workers or offsite persons. In addition to aerosol emissions, irrigation transfers pathogens to CROP SURFACE (14) and to SOIL SURFACE WATER (11).

SOIL SURFACE WATER (11) represents any irrigation water or rainfall in contact with the ground prior to infiltration. This compartment describes the temporary suspension of pathogens in such a water layer and their subsequent transfer to CROP SURFACE (14) or to SOIL SURFACE (4). Process functions are the same as for other water compartments.

OFFSITE WELL (12*) is the exposure site for a human receptor drinking 2 L/day of contaminated water whose pathogens have been transported through groundwater. Process functions are the same as for groundwater. The groundwater transport subroutine supplies the concentration of pathogens in the well at a user-specified distance from the source. No transfers out of the compartment are specified because it is an exposure compartment only.

AEROSOLS (13*) describes fugitive emissions from spray irrigation, which occurs at a default rate of 0.5 cm/hour for 5 hours. The source of irrigation water producing AEROSOLS can be an onsite well (i.e., GROUNDWATER (9)) or liquid sludge. Process functions are described in Chapter 5, as is the Gaussian-plume model used to calculate concentrations of airborne microbes downwind. The human receptor is an onsite worker or a person offsite who is exposed during the time of irrigation.

CROP SURFACE (14) describes contamination of vegetable or forage crops by transfer of user-specified amounts to or from SOIL SURFACE (4), from IRRIGATION WATER (10), or to or from SOIL SURFACE WATER (11). Process functions are not well characterized, but default values were chosen to be the same as in the soil surface.

The following summaries describe each of the five modeled practices.

3.3. APPLICATION OF LIQUID SLUDGE FOR PRODUCTION OF COMMERCIAL CROPS FOR HUMAN CONSUMPTION (PRACTICE I)

Liquid sludge may be applied as fertilizer/soil conditioner for the production of agricultural crops for human consumption or for animal forage or prepared feed. Both existing (40 CFR 257.3-6) and proposed (U.S. EPA, 1989b) regulations prohibit direct application of sewage sludge to crop surfaces. Therefore, this model practice is designed for a single application of liquid sludge, which is incorporated into the soil before the crop is planted. Regulations also require various waiting periods before the planting of crops that will be consumed uncooked by humans. These restrictions, however, are optional in the model and can be tested.

The following description summarizes the practice-specific compartments, processes and transfers.

APPLICATION (1) represents the application of liquid sludge to a field (size given by AREA [P(7)], default 10 ha). The pathogen concentration (ASCRS [P(1)], Table A-2) and application rate (APRATE [P(2)], default 10,000 kg/ha, or 10 T/ha) can be entered by the user of the model. Spray application is not expected to be the method of choice for applying sludge in this practice, because installing sprayers for a single use would not be practical. The user, however, may choose this option by specifying APMETH [P(6)] = -1. Spread-flow application is the default method of application (APMETH = 1). The default application rate (APRATE [P(2)]) is 10 T/ha, which the model treats as a single application. Subsurface injection can be chosen by specifying APMETH = 0. In this case, no sludge pathogens are introduced to the soil surface except by irrigation.

During APPLICATION, inactivation of pathogens will occur at a rate characteristic of the organism in soil at the expected soil surface temperature. This temperature is taken to be 5°C above ambient air temperature (TEMP [P(8)]) to allow for surface warming (Brady, 1974; USDA, 1975). It is assumed that surface-applied liquid sludge is absorbed by the upper 5 cm of soil surface during this time. The default time for transfer from APPLICATION (1) to INCORPORATION (2) is 24 hours, which allows a field treated with liquid sludge to dry sufficiently to plow or cultivate. Alternatively, if the injection option is chosen, transfer to SUBSURFACE SOIL (8) occurs at 10 hours.

Aerosol emissions are modeled as the transfer of liquid sludge from APPLICATION (1) to APPLICATION/TILLING EMISSIONS (3*) only if spray application is specified.

INCORPORATION (2) involves the mixing, by plowing or cultivation, of the sludge and sludge-associated pathogens evenly throughout the upper 15 cm of soil. Particulate emissions generated by cultivation are represented by a transfer from INCORPORATION to APPLICATION/TILLING EMISSIONS (3*) beginning at hour 24, and extending for enough time to cultivate the field (at a rate of 5 ha/hour). At the end of this time, all remaining pathogens are transferred to SOIL SURFACE (4). During incorporation, pathogens will be inactivated at a rate characteristic of the organism in moist soil at the expected soil surface temperature. This temperature is taken to be 5°C above ambient air temperature (TEMP [P(8)]) to allow for surface warming (Brady, 1974; USDA, 1975). INCORPORATION (2) dilutes the pathogens by mixing the sludge with soil; the concentration of pathogens becomes (ASCRS pathogens/kg $*$ APRATE kg/ha)/($2*10^6$ kg/ha).

APPLICATION/TILLING EMISSIONS (3*) is an exposure compartment that receives the dust, or suspended particulates, generated by tilling the dried sludge or sludge-soil mixture. Tilling occurs at INCORPORATION (2) and at times specified by TCULT

[P(67)]. Additional tilling does not occur if TCULT = -2, but can be called biweekly (TCULT = 0) or at a single time given by TCULT > 0. The concentration of airborne particulates in this compartment is calculated using an equation for dust emissions during cultivation (U.S. EPA, 1985b). The source strength and exposure equations are described in Chapter 5 and in Volume II: User's Manual. This compartment is strictly an exposure compartment, and no die-off of pathogens is assumed. Exposure calculations are made by Subroutine RISK.

This compartment also receives pathogens from aerosols generated by spray application of liquid sludge if APMETH [P(6)] = -1. The source strength of the aerosol is calculated from the rate of application and concentration of pathogens in the liquid sludge (Section 4.6).

SOIL SURFACE (4) describes the processes occurring in the upper 15 cm of the soil layer. No practice-specific differences from the general description above are expected.

WIND-GENERATED PARTICULATES (5*) describes the airborne particulates generated by wind at a user-supplied time TWIND [P(23)] (default 60 hours). Die-off rates are those expected for pathogens in air-dried soil at the ambient temperature. The exposed individual is standing in the field or at a user-specified distance (default 200 m) downwind from the field during a windstorm. The wind-generated exposure is calculated from user-specified values for duration (DWIND [P(24)]) and intensity (WINDSP [P(25)]) of the windstorm (default values 6 hours at 18 m/sec (40 mph)) assuming, as a worst case, that there is no plant cover on the soil surface (COVER [P(30)] = 0). Exposure calculations are made by Subroutine RISK.

SURFACE RUNOFF (6*) describes an onsite pond containing pathogens transferred from SOIL SURFACE (4) by surface runoff and sediment transport after rainfall. The human receptor is an individual who incidentally ingests 0.1 L of contaminated water while swimming in the pond. Exposure calculations are made by Subroutine RISK.

DIRECT CONTACT (7*) is the exposure compartment for a worker or for a child less than 5 years old who plays in or walks through the field, incidentally ingesting 0.1 g of soil. This human receptor represents the worst-case example of an individual contacting contaminated soil or soiled clothing or implements. Exposure calculations are made by Subroutine RISK.

SUBSURFACE SOIL (8) describes the processes and transfers for pathogens in the subsurface soil between 15 cm depth and the water table. It also serves as the incorporation site for subsurface injection of liquid sludge (APMETH [P(6)] = 0). Pathogens are transferred from SOIL SURFACE by leaching after a rain or irrigation event. The fraction of pathogens transferred is a user-supplied value (SUBSOL [P(44)], default pathogen-specific (Table A-2)). Die-off rates are characteristic of pathogens in soil at the ambient temperature.

GROUNDWATER (9) describes the flow of pathogens in the saturated zone. Process functions are the same as for other water compartments. The volume of water represented by GROUNDWATER (9) is calculated from the average thickness in meters of the aquifer (variable AQUIFR [P(9)], default 10), the average porosity of the aquifer (POROS [P(10)], default 0.3) and the surface area. The model assumes that pathogens are uniformly distributed throughout the aquifer. Transfers occur to IRRIGATION WATER (10) if the water is needed for irrigation (which is the default condition). Transfers to OFFSITE WELL (12*) for use as drinking water are described by Subroutine GRDWTR, the modified solute transport model.

IRRIGATION WATER (10) describes the transfers of pathogen-contaminated water used for irrigation. No processes are associated with this compartment because it is intended as a transition compartment. The default source of IRRIGATION WATER (10) is GROUNDWATER (9) from an onsite well, with no contribution from other sources (DILIRR [P(18)] = 0). An additional source of contaminated irrigation water can be modeled by specifying its relative contribution ($0 < \text{DILIRR} \leq 1$). The concentration of pathogens in this source is given by the variable COUNT [P(22)]. Transfer to AEROSOL (13*) is possible if spray irrigation is used; this is the default option because spread-flow irrigation would not be expected to cause a significant exposure to workers or offsite persons. Irrigation transfers pathogens to SOIL SURFACE WATER (11) and to CROP SURFACE (14) after sufficient time has passed to allow a crop surface to form (TCROP [P(68)], default 720 hours). SOIL SURFACE WATER (11) is the compartment representing water in contact with the ground prior to infiltration. Transfers occur to SOIL SURFACE (4) and to CROP SURFACE (14). Die-off rates are assumed to be the same as for pathogens in water.

OFFSITE WELL (12*) is the exposure site for a human receptor drinking 2 L/day of contaminated water whose pathogens have been transported through groundwater. The groundwater transport subroutine (Subroutine GRDWTR) supplies the concentration of pathogens in the well at a user-specified distance from the source (default value 50 m). Exposure calculations are made by Subroutine RISK.

IRRIGATION AEROSOLS (13*) describes fugitive emissions from spray irrigation, done at a rate of IRRATE [P(20)] cm/hour (default 0.5) for 5 hours, NIRRIG [P(19)] times per week (default=2). Process functions are described in Chapter 5, as is the

Gaussian-plume model used to calculate concentrations of airborne microbes downwind. The human receptor is an onsite worker or a person offsite who is exposed during the time of irrigation. Exposure calculations are made by Subroutine RISK.

CROP SURFACE (14) describes contamination of vegetable crops by transfer of pathogens from SOIL SURFACE (4), IRRIGATION WATER (10) or SOIL SURFACE WATER (11). No transfers to CROP SURFACE occur before TCROP [P(68)], the time at which the plants have emerged (default 720 hours). Vegetables can be grown aboveground, on-ground or below-ground. These are represented by tomatoes, zucchini and carrots, respectively. Pathogen concentrations are determined as number/crop unit for each sludge management practice. Process functions are assumed to be influenced by drying, thermal inactivation and solar radiation and are thus most characteristic of pathogens in surface soil (5°C above ambient temperature).

HARVESTING (15) occurs at THARV [P(69)] (default 1800 hours). At this time, all pathogens remaining on CROP SURFACE (14) are transferred to HARVESTING (15), which represents a single harvest of all of the crop. The same process functions apply as in CROP SURFACE (14). The crop is held for 24 hours before being processed. The number of pathogens is then transferred to COMMERCIAL CROPS (16*).

COMMERCIAL CROPS (16*) is the compartment in which further processing takes place. The number of pathogens/crop unit following processing is calculated in this compartment and is the figure used in the vegetable-exposure risk calculations. A 24-hour pathogen exposure is computed by Subroutine VEG.

Before being consumed, vegetables normally are processed in some way. Included in the program is a series of user-selectable processing steps. The user has the option of choosing any or all processing steps, listed in Table A-4, and of specifying some conditions within processing steps. In the default condition, the human receptor consumes minimally prepared vegetables (washed, but not peeled or cooked) at a rate of 81 g tomatoes, 80 g zucchini or 43 g carrots per eating occasion (Pao et al., 1982).

3.4. APPLICATION OF LIQUID SLUDGE TO GRAZED PASTURES (PRACTICE II)

In this practice, liquid sludge is applied as fertilizer, soil conditioner and irrigation water for the production of forage crops for pasture. This model practice is designed for repeated applications of liquid sludge on a field with a standing forage crop used for pasture. Spray irrigation is the method of choice for this practice since it is effective for delivering large amounts of sludge to a large area. In this way, the pasture is also used as a final treatment and disposal system for the treated sludge. An irrigation rate of 0.5 cm/hour for 5 hours for a total depth of 2.5 cm twice weekly is used as the default condition for operation of the model, but the rate (IRRATE [P(20)]), the total weekly depth (DEPTH [P(21)]) and the number of times per week (NIRRIG [P(19)]) can be changed by the user. A sludge solids concentration of 5% is assumed.

The model assumes that each hectare of pasture supports 12 head of cattle, although both area and herd size may be varied. This may be a higher density than is the common practice for fields that receive no irrigation, but with adequate irrigation, sufficient forage is expected to be produced. Current and proposed regulations require various waiting periods before animals can be grazed. These requirements can be tested by the model.

APPLICATION (1) represents the application of liquid sludge to a pasture (size given by AREA [P(7)], default 10 ha). The pathogen concentration (ASCRS [P(1)], Table A-2) and application rate (APRATE [P(2)], default 12.5 T/ha) can be entered by the user of the model. Spray application is expected to be the method of choice for applying sludge in this practice (APMETH [P(6)] = -1), in which case the initial application is assumed to be the same as for one day's irrigation (2.5 cm depth = 250 m^3/ha, or 12.5 T/ha at 5% sludge solids). However, the user may choose spread-flow application (APMETH = 1) or subsurface injection (APMETH = 0).

During APPLICATION (1), inactivation of pathogens will occur at a rate characteristic of the organism in soil at the expected soil surface temperature. This temperature is taken to be 5°C above ambient air temperature (TEMP [P(8)]) to allow for surface warming (Brady, 1974; USDA, 1975). It is assumed that surface-applied liquid sludge is absorbed by the upper 5 cm of soil surface during this time. The assumed time for transfer from APPLICATION (1) to SOIL SURFACE (4) is 15 hours.

INCORPORATION (2) is omitted in this practice because incorporation by cultivation is not reasonable when there is a standing crop.

APPLICATION/TILLING EMISSIONS (3*) is an exposure compartment used to calculate exposures to aerosol emissions generated by application of liquid sludge if the spray option (APMETH [P(6)] = -1) is used. The source strength of the aerosol is calculated from the rate of application and concentration of pathogens in the liquid sludge (Section 4.6). Tilling of pasture crops is not expected to occur, so no dust emissions are calculated. Exposure calculations are made by Subroutine RISK.

SOIL SURFACE (4) describes the processes occurring in the upper soil layer. On the assumption that SOIL SURFACE will not be as deep in this practice as in practices with an incorporation step, a value of 5 cm, corresponding to $6.7 \cdot 10^5$ kg/ha, has been assigned to its depth. Therefore, the dilution of pathogen-laden sludge by soil is less than in Practices I, IV and V. The pathogen load is assumed to be uniformly distributed throughout this layer. Process functions are those given for pathogens in soil.

WIND-GENERATED PARTICULATES (5*) describes the airborne particulates generated by wind at a user-supplied time TWIND [P(23)] (default 60 hours). Die-off rates are those expected for pathogens in air-dried soil at the ambient temperature. The exposed individual is standing in the field or at a user-specified distance downwind from the field during a windstorm. The wind-generated exposure is calculated from user-specified values for duration (DWIND [P(24)]) and severity (WINDSP [P(25)]) of the windstorm (default values 6 hours at 18 m/sec (40 mph)). The fraction of soil surface with plant cover in this practice is COVER [P(30)] = 0.9. Exposure calculations are made by Subroutine RISK.

SURFACE RUNOFF (6*) describes an onsite pond containing pathogens transferred from SOIL SURFACE (4) by surface runoff and sediment transport after rainfall. The human receptor incidentally ingests 0.1 L of contaminated water while swimming in the pond. This compartment is also an exposure compartment for cattle drinking 20 L of water daily. Exposure calculations are made by Subroutine RISK.

DIRECT CONTACT (7*) is the exposure compartment for a worker or for a child less than 5 years old who plays in or walks through the field, incidentally ingesting 0.1 g of soil and 0.1 g of vegetation. This human receptor represents the worst-case example of an individual contacting contaminated soil or soiled clothing or implements. Exposure calculations are made by Subroutine RISK.

SUBSURFACE SOIL (8) describes the processes and transfers for pathogens in the subsurface soil between 5 cm depth and the water table. It also serves as the incorporation site for subsurface injection of liquid sludge (APMETH [P(6)] = 0).

GROUNDWATER (9) describes the flow of pathogens in the saturated zone. Process functions are the same as for other water compartments. The volume of water represented by GROUNDWATER is calculated from the average thickness in meters of the aquifer (variable AQUIFR [P(9)], default 10), the average porosity of the aquifer (POROS [P(10), default 0.3) and the surface area. The distribution of pathogens throughout the aquifer is assumed to be uniform. Transfers occur to IRRIGATION WATER (10) if the water is needed for irrigation (which is the default condition). Transfers to OFFSITE WELL (12*) for use as drinking water are described by Subroutine GRDWTR, the modified solute transport model.

IRRIGATION WATER (10) describes the transfers of pathogen-contaminated water used for irrigation. No processes are associated with this compartment because it is intended as a transition compartment. IRRIGATION WATER comes by default from a source of liquid sludge (COUNT [P(22)] = 12.5 T/ha $*$ $5*10^4$ pathogens/kg = $6.25*10^8$ pathogens/kg and DILIRR = 1); the user may specify irrigation from an onsite well fed by GROUNDWATER (DILIRR [P(18)] = 0). Transfer to AEROSOL (13*) occurs if spray irrigation is used; this is the default option because spread-flow irrigation would not be expected to cause a significant exposure to workers or offsite persons. Irrigation transfers 10% of the pathogens to CROP SURFACE (14) and 90% to SOIL SURFACE WATER (11).

SOIL SURFACE WATER (11) is the compartment serving as a source and recipient of pathogens for SOIL SURFACE (4) and for CROP SURFACE (14). It describes the suspension of crop- and soil-associated pathogens, as well as those transferred by irrigation, in the layer of water resulting from irrigation or rainfall. It also describes their transfer back to either SOIL SURFACE (4) or CROP SURFACE (14). The residence time for pathogens in this compartment is determined by the depth of water and by the infiltration rate. The process functions are those associated with other water compartments.

OFFSITE WELL (12*) is the exposure site for a human receptor drinking 2 L/day of contaminated water whose pathogens have been transported through groundwater. The groundwater transport subroutine (Subroutine GRDWTR) supplies the concentration of pathogens in the well at a user-specified distance from the source (default value 50 m). Exposure calculations are made by Subroutine RISK.

IRRIGATION AEROSOLS (13*) describes fugitive emissions from spray irrigation, done at a rate of IRRATE [P(20)] cm/hour (default 0.5) for 5 hours, NIRRIG [P(19)] times per week. The default source of irrigation water producing IRRIGATION AEROSOLS (13*) is liquid sludge, although it may be GROUNDWATER (9). Process functions are described in Chapter 5, as is the Gaussian-plume model used to calculate concentrations of airborne microbes downwind. The human receptor is an onsite worker or a person offsite who is exposed during the time of irrigation. Exposure calculations are made by Subroutine RISK.

CROP SURFACE (14) describes contamination of the forage crop by transfer of pathogens from SOIL SURFACE (4), IRRIGATION WATER (10) or SOIL SURFACE WATER (11). The model assumes that 10% of the solids in liquid sludge applied as IRRIGATION WATER are retained by the plant surfaces and 90% reach SOIL SURFACE

(ASLSUR [P(41)] = 0.9). Process functions are assumed to be influenced by drying, thermal inactivation and solar radiation, and are thus characteristic of pathogens in surface soil (5°C above ambient temperature).

HARVESTING (15) is not applicable in this practice.

COMMERCIAL CROP (16*) is not applicable in this practice.

ANIMAL CONSUMPTION (17) describes the ingestion of CROP SURFACE (14) by cattle grazing in the pasture. Cattle consume a specified amount of forage (default FORAG [P(81)] = 7 kg dry wt) daily, as well as an amount of pathogen-contaminated soil (default SCNSMP [P(83)] = 1.1 kg). The fraction of CROP SURFACE (14) pathogens consumed per cow is given by the ratio of FORAG [P(81)] to the forage yield per hectare, default value 1.6 kg/m^2 (Whittaker, 1975).

The model assumes that because of the high acidity of the cow's rumen and the effects of competition by rumen bacteria, infection of the cow by bacterial pathogens will occur only if the number of bacteria ingested by each cow is greater than $1*10^8$/day. Human enteroviruses and parasites from domestic sewage are assumed not to be infective for cattle. Transfers from ANIMAL CONSUMPTION (17) are to MEAT (18*), MANURE (19) and MILK (20*).

MEAT (18*) is the compartment describing transfer of pathogens from ANIMAL CONSUMPTION (17) to meat. The human receptor is assumed to consume 0.256 kg of meat daily (U.S. FDA, 1978). The model allows for inactivation of pathogens in meat by cooking, assuming reasonable cooking times and temperatures.

Pathogens can be transferred to MEAT (18*) by systemic infection with bacterial pathogens. The default value for this transfer (DTCTMT [P(59)]) is zero since no data could be found quantifying the contamination of meat from a systemic Salmonella infection, and neither Ascaris nor poliovirus should transfer from the gut of the cattle. The user can assign a value to DTCTMT if contamination of MEAT by a systemic infection is assumed. The transfer would occur daily but only for the Salmonella pathogen type.

If the beef cattle option is chosen (variable CATTLE [P(78)] = -1), the cattle grazing the pasture will be slaughtered at day TSLOTR [P(85)]. At slaughter, each animal becomes 270 kg of MEAT. When cattle are butchered, the MEAT is often contaminated by enteric bacteria present in the gut of the cattle. This transfer is modeled as being from MANURE (19) to HIDE (21) and then MEAT (18*). HTM [P(64)], the fraction of pathogens in HIDE transferred to MEAT at time of slaughter (TSLOTR [P(85)]), applies to all three pathogen types. There are no transfers out of this compartment, but the pathogen population is used in meat exposure risk calculations. After slaughter, no risks are assumed to occur from non-meat portions of the carcass.

MANURE (19) describes the source of contamination of MEAT (18*) and MILK (20*) with pathogens excreted by an infected cow. Enteroviruses and parasites do not enter this compartment because they are assumed not to infect cattle. Pathogenic bacteria appear in the compartment if the number in ANIMAL CONSUMPTION (17) exceeds $1*10^8$/day/cow. Cattle are assumed to produce 4 kg/day DW of manure, and a cow infected with an enteric pathogen will excrete $1*10^9$ bacteria/g. Pathogens from MANURE are transferred to SOIL SURFACE (4), HIDE (21) and UDDER (22).

MILK (20*) is the compartment describing production and consumption of milk from cattle pastured on the sludge-amended field when the dairy cattle option is chosen (CATTLE [P(78)] = +1). This is the default condition. In this practice, the default size of the herd is 12 head/ha, and a yield of 15 L of milk/cow/day is assumed. Milking occurs twice daily and, in commercial practices, the milk is immediately chilled and held at 1°C until pasteurization. However, as described in Chapter 4, the default condition is for consumption of raw milk because commercial production of milk poses an extremely small hazard of exposure to pathogens.

In the model, pathogens can be transferred to MILK (20*) directly from the compartment ANIMAL CONSUMPTION (17). This transfer will simulate the possible effects of a systemic Salmonella infection. The user must supply a value for DTCTMK [P(60)], the variable which specifies the fraction of the pathogens transferred from the ANIMAL CONSUMPTION compartment. The default value for this variable is zero because transfer of pathogens from the blood of even a septicemic cow to milk is unlikely. Neither Ascaris nor enteroviruses are known to infect cattle.

In the model, pathogens resulting from using contaminated utensils and from careless handling are combined as a transfer, which occurs at each milking, from the manure-contaminated UDDER (22) compartment. All three pathogens can enter MILK (20*) by this route. There are no transfers out of this compartment, but the pathogen population is used in the milk-exposure risk calculation.

The default condition will model the consumption of raw milk which has been stored for 24 hours. This condition will give a worst-case probability of infection. Exposure calculations are made by Subroutine RISK, which assumes that the human receptor consumes 2 kg milk/day, roughly three times the national average milk consumption (U.S. FDA, 1978).

HIDE (21) describes the route of transfer of pathogenic enteric bacteria from

MANURE to MEAT. A fraction of pathogens from MANURE (TMTH [P(62)], default 0.001) is transferred hourly to HIDE and has an hourly die-off rate of 0.04. At time TSLOTR [P(85)], a fraction of the pathogens in HIDE (default HTM = 0.1) is transferred to MEAT (18*).

UDDER (22) provides for an indirect transfer of pathogens from manure to MILK. A fraction of pathogens from MANURE (TMTU [P(63)], default 0.001) is transferred hourly to UDDER, from which the pathogens have an hourly removal rate of 0.04. Therefore, the number of pathogens in UDDER is zero unless infection of the cow has occurred. At each milking, a fraction (UTM [P(65)], default 0.05) of the manure on the udder is assumed to fall into the milk. These pathogens provide the exposure associated with raw milk in Subroutine RISK.

3.5. APPLICATION OF LIQUID SLUDGE FOR PRODUCTION OF CROPS PROCESSED BEFORE ANIMAL CONSUMPTION (PRACTICE III)

In this practice, liquid sludge is applied as fertilizer, soil conditioner and irrigation water for the production of forage crops to be processed and stored for animal feed. This model practice is designed for repeated applications of liquid sludge on a field with a standing forage crop. The model assumes that spray irrigation will be used for the application of liquid sludge in this practice because this method is effective for delivering large amounts of sludge to a large area. In this way, the field is also used as a final treatment and disposal system for the treated sludge. An irrigation rate of 0.5 cm/hour for 5 hours for a total depth of 2.5 cm twice weekly is used as the default condition for operation of the model, but the rate (IRRATE [P(20)]), the total weekly depth (DEPTH [P(21)]) and the number of irrigations per week (NIRRIG [P(19)]) can be changed by the user. A sludge solids concentration of 5% is assumed.

APPLICATION (1) represents the application of liquid sludge to a field (size given by AREA [P(7)], default 10 ha). The pathogen concentration (ASCRS [P(1)], default pathogen-specific (Table A-2)) and application rate (APRATE [P(2)], default 12.5 T/ha) are variables that can be entered by the user of the model. Spray application is expected to be the method of choice for applying sludge in this practice (APMETH [P(6)] = -1), in which case the initial application is assumed to be the same as for one day's irrigation (2.5 cm depth = 250 m^3/ha, or 12.5 T/ha at 5% sludge solids). The user, however, may choose spread-flow application (APMETH = 1) or subsurface injection (APMETH = 0).

During APPLICATION (1), inactivation of pathogens will occur at a rate characteristic of the organism in soil at the expected soil surface temperature. This temperature is taken to be 5°C above ambient air temperature (TEMP [P(8)]) to allow for surface warming (Brady, 1974; USDA, 1975). It is assumed that surface-applied liquid sludge is absorbed by the upper 5 cm of soil surface during this time. The default time for transfer from APPLICATION (1) to SOIL SURFACE (4) is 1 hour.

INCORPORATION (2) is omitted in this practice because incorporation by cultivation is not reasonable when there is a standing crop.

APPLICATION/TILLING EMISSIONS (3*) is an exposure compartment used to calculate exposures to suspended particulates generated by application of liquid sludge if the spray option (APMETH [P(6)] = -1) is used. Aerosol emissions are modeled as the transfer of liquid sludge from APPLICATION to APPLICATION/TILLING EMISSIONS (3*) only if spray application is specified. The source strength of the aerosol is calculated from the rate of application and concentration of pathogens in the liquid sludge (Section 4.6). Tilling of field crops is not expected to occur, so no tilling emissions are calculated. Exposure calculations are made by Subroutine RISK.

SOIL SURFACE (4) describes the processes occurring in the upper soil layer. It is assumed that SOIL SURFACE will not be as deep in this practice as in Practices I, IV and V because there is no incorporation step, and a value of 5 cm, corresponding to $6.7 * 10^5$ kg/ha, has been assigned to its depth. Therefore, the dilution of pathogen-laden sludge by soil is less than in Practices I, IV and V. The pathogen load is assumed to be uniformly distributed throughout this layer. Process functions are those given for pathogens in soil.

WIND-GENERATED PARTICULATES (5*) describes the airborne particulates generated by wind at a user-supplied time TWIND [P(23)] (default 60 hours). Die-off rates are those expected for pathogens in air-dried soil at the ambient temperature. The exposed individual is standing in the field or at a user-specified distance downwind from the field during a windstorm. The wind-generated exposure is calculated from user-specified values for duration (DWIND [P(24)]) and severity (WINDSP [P(25)]) of the windstorm (default values 6 hours at 18 m/sec (40 mph)). The fraction of soil surface with plant cover in this practice is COVER [P(30)] = 0.9. Exposure calculations are made by Subroutine RISK.

SURFACE RUNOFF (6*) describes an onsite pond containing pathogens transferred from SOIL SURFACE (4) by surface runoff and sediment transport after rainfall. The human receptor incidentally ingests 0.1 L of contaminated water while swimming in the pond. Exposure calculations are made by Subroutine RISK.

DIRECT CONTACT (7*) is the exposure compartment for a worker or for a child younger than 5 years old who plays in or walks through the field, incidentally ingesting 0.1 g of soil and 0.1 g of crop surface. This human receptor represents the worst-case example of an individual contacting contaminated soil, soiled clothing or implements. Exposure calculations are made by Subroutine RISK.

SUBSURFACE SOIL (8) describes the processes and transfers for pathogens in the subsurface soil between 5 cm depth and the water table. It also serves as the incorporation site for subsurface injection of liquid sludge (APMETH [P(6)]= 0).

GROUNDWATER (9) describes the flow of pathogens in the saturated zone. Process functions are the same as for other water compartments. The volume of water represented by GROUNDWATER is calculated from the average thickness in meters of the aquifer (variable AQUIFR [P(9)], default 10), the average porosity of the aquifer ([P(10), default 0.3) and the surface area. Pathogens are assumed to be distributed uniformly throughout the aquifer. Transfers occur to IRRIGATION WATER (10) if the water is needed for irrigation (which is the default condition). Transfers to OFFSITE WELL (12*) for use as drinking water are described by Subroutine GRDWTR, the modified solute transport model.

IRRIGATION WATER (10) describes the transfers of pathogen-contaminated water used for irrigation. No processes are associated with this compartment because it is intended as a transition compartment. IRRIGATION WATER comes by default from a source of treated liquid sludge (COUNT [P(22)] = $6.25*10^8$ pathogens/kg and DILIRR [P(18)] = 1); the user may specify irrigation from an onsite well fed by GROUNDWATER (DILIRR = 0). Transfer to AEROSOL (13*) occurs if spray irrigation is used; this is the default option because spread-flow irrigation would not be expected to cause a significant exposure to workers or offsite persons. Irrigation transfers 10% of the pathogens to CROP SURFACE (14) and 90% to SOIL SURFACE WATER (11) (ASLSUR [P(41)] = 0.9).

SOIL SURFACE WATER (11) is the compartment serving as a source of pathogens for SOIL SURFACE (4) and for CROP SURFACE (14). It describes the suspension of crop- and soil-associated pathogens, as well as those transferred by irrigation, in the layer of water resulting from irrigation or rainfall. It also describes their transfer back to either SOIL SURFACE (4) or CROP SURFACE (14). The residence time for pathogens in this compartment is determined by the depth of water and by the infiltration rate. The process functions are those associated with other water compartments.

OFFSITE WELL (12*) is the exposure site for a human receptor drinking 2 L/day of contaminated water whose pathogens have been transported through groundwater. The groundwater transport subroutine (Subroutine GRDWTR) supplies the concentration of pathogens in the well at a user-specified distance from the source (default value 50 m). Exposure calculations are made by Subroutine RISK.

IRRIGATION AEROSOLS (13*) describes fugitive emissions from spray irrigation, done at a rate of IRRATE [P(20)] cm/hour (default 0.5) for 5 hours, NIRRIG [P(19)] times per week. The default source of irrigation water producing IRRIGATION AEROSOLS (13*) is treated liquid sludge, although it may be GROUNDWATER. Process functions are described in Chapter 5, as is the Gaussian-plume model used to calculate concentrations of airborne microbes downwind. The human receptor is an onsite worker or a person offsite who is exposed during the time of irrigation. Exposure calculations are made by Subroutine RISK.

CROP SURFACE (14) describes contamination of the forage crop by transfer of pathogens from SOIL SURFACE (4), IRRIGATION WATER (10) or SOIL SURFACE WATER (11). It is assumed that 10% of the solids in liquid sludge applied as IRRIGATION WATER are retained by the plant surfaces and 90% reach SOIL SURFACE (ASLSUR [P(41)] = 0.9). Process functions are assumed to be influenced by drying, thermal inactivation and solar radiation and are thus characteristic of pathogens in surface soil (5°C above ambient temperature).

HARVESTING, PROCESSING AND STORAGE (15) describes the processes and transfers associated with cutting, processing and storing the forage crop. At time THARV ([P(69)], default 720 hours), all pathogens remaining in CROP SURFACE (14) are transferred to this compartment. The crop is baled or rolled and removed from the field for storage for a period of time specified by STORAG [P(80)]. After the storage period, transfers to ANIMAL CONSUMPTION (17) begin; the number of pathogens transferred each day is proportional to the amount of crop fed to the cattle, as described in ANIMAL CONSUMPTION. Process functions are characteristic of pathogens in dry soil at the ambient temperature.

COMMERCIAL CROP (16*) is not applicable in this practice.

ANIMAL CONSUMPTION (17) describes the ingestion of the stored crop by cattle. Cattle consume a specified amount of forage (default FORAG [P(81)] = 7 kg dry wt) daily, as well as an amount of pathogen-contaminated soil (default SCNSMP [P(83)] = 1.1 kg). The variable ALFALF [P(82)] indicates the percentage of total forage that is the harvested crop. The fraction of HARVESTING, PROCESSING AND STORAGE (15) pathogens consumed per cow is given by the ratio of contaminated FORAG to the forage yield per hectare, default value 1.6 kg/m^2 (Whittaker, 1975). The feeding of contaminated forage to the cattle ends after a specified number of days, FATTEN [P(84)], or when the total yield has been consumed.

The model assumes that because of the high acidity of the cow's rumen and the effects of competition by rumen bacteria, infection of the cow by bacterial pathogens will occur only if the number of bacteria ingested by each cow is greater than $1*10^8$/day. Human enteroviruses and parasites from domestic sewage are assumed not to be infective for cattle. Transfers from ANIMAL CONSUMPTION (17) are to MEAT (18*), MANURE (19) and MILK (20*).

MEAT (18*) is the compartment describing transfer of pathogens from cattle to meat. The human receptor is assumed to consume 0.256 kg of meat daily (U.S. FDA, 1978). The model allows for inactivation of pathogens in meat by cooking, assuming reasonable cooking times and temperatures.

Pathogens can be transferred to MEAT (18*) by systemic infection with bacterial pathogens. The default value for this transfer (DTCTMT [P(59)]) is zero since no data could be found quantifying the contamination of meat from a systemic Salmonella infection, and neither Ascaris nor poliovirus should transfer from the gut of the cattle. The user can assign a value to DTCTMT [P(59)] if contamination of MEAT by a systemic infection is desired. The transfer would occur daily but only for the Salmonella pathogen type.

If the beef cattle option is chosen (CATTLE [P(78)] = -1), the cattle fed the stored forage will be slaughtered at day TSLOTR [P(85)]. At slaughter, each animal becomes 270 kg of MEAT (18*). When cattle are butchered, the MEAT (18*) is often contaminated by enteric bacteria present in the gut of the cattle. This transfer is modeled as being from MANURE (19) to HIDE (21) and then MEAT (18*). HTM [P(64)], the fraction of HIDE (21) pathogens transferred to MEAT at time of slaughter (TSLOTR [P(85)]), applies to all three pathogen types. There are no transfers out of this compartment, but the pathogen population is used in meat exposure risk calculations. After slaughter, no risks are assumed to occur from non-meat portions of the carcass.

MANURE (19) describes the source of contamination of MEAT (18*) and MILK (20*) with pathogens excreted by an infected cow. Enteroviruses and parasites do not enter this compartment because they are assumed not to infect cattle. Pathogenic bacteria appear in the compartment if the number in ANIMAL CONSUMPTION (17) exceeds $1*10^8$/day/cow. The model assumes that cattle produce 4 kg (dry wt) of manure per day and that a cow infected with an enteric pathogen will excrete $1*10^9$ bacteria/g. Pathogens from MANURE (19) are transferred to HIDE (21) and UDDER (22).

MILK (20*) is the compartment describing production and consumption of milk from cattle fed stored forage crops from the sludge-amended field when the dairy cattle option is chosen (CATTLE [P(78)] = +1). This is the default condition. In this practice, the size of the herd is 12 head, and a yield of 15 L of milk/day is assumed. Milking occurs twice daily, and, in commercial practices, the milk is immediately chilled and held at 1°C until pasteurization. However, as described in Chapter 4, the default condition is for consumption of raw milk because commercial production of milk poses an extremely small hazard of exposure to pathogens.

In the model, pathogens can be transferred to MILK (20*) directly from the compartment ANIMAL CONSUMPTION (17). This transfer will simulate the possible effects of a systemic Salmonella infection. The user must supply a value for DTCTMK [P(60)], the variable that specifies the fraction of the pathogens transferred from the ANIMAL CONSUMPTION (17) compartment. The default value for this variable is zero because transfer of pathogens from the blood of even a septicemic cow to milk is unlikely. Neither Ascaris nor enteroviruses are known to infect cattle.

In the model, pathogens resulting from using contaminated utensils and from careless handling are combined as a transfer, which occurs at each milking, from the manure-contaminated UDDER (22) compartment. All three pathogens can enter MILK (20*) by this route. There are no transfers out of this compartment, but the pathogen population is used in milk-exposure risk calculation.

The default condition will model the consumption of raw milk which has been stored for 24 hours. This condition will give a worst-case probability of infection. Exposure calculations are made by Subroutine MILK, which assumes that the human receptor consumes 2 kg milk/day, roughly three times the national average milk consumption (U.S. FDA, 1978).

HIDE (21) describes the route of transfer of pathogenic enteric bacteria from MANURE (19) to MEAT (18*). A fraction of pathogens from MANURE (19) (TMTH [P(62)], default 0.001) is transferred hourly to HIDE. Pathogens in HIDE (21) have an hourly removal rate of 0.04. At time TSLOTR [P(85)], a fraction of the pathogens in HIDE (21) (default HTM [P(64)] = 0.1) is transferred to MEAT (18*).

UDDER (22) provides for an indirect transfer of pathogens from manure to MILK. A fraction of pathogens from MANURE (19) (TMTU [P(63)], default 0.001) is transferred hourly to UDDER. Therefore, the number of pathogens in UDDER is zero unless infection of the cow has occurred. Pathogens in UDDER (22) have an hourly removal rate of 0.04. At each milking, a fraction (UTM [P(65)], default 0.05) of the manure on the udder is assumed to fall into the milk. These pathogens provide the exposure associated with raw milk in MILK (20*).

3.6. APPLICATION OF DRIED OR COMPOSTED SLUDGE TO RESIDENTIAL VEGETABLE GARDENS (PRACTICE IV)

Dried or composted treated sludge may be made available to the public as a bulk or bagged product to be sold or given away. It may be used as fertilizer or soil conditioner in the production of domestic garden crops for human consumption. Although some studies have shown that composting is highly effective in removing pathogens from sludge (Wiley and Westerberg, 1969), other studies have shown that bacterial pathogens may grow in dried or composted sludge to concentrations of 1×10^6 organisms/kg dry weight (U.S. EPA, 1988). Exposure of individuals to materials used in home gardening would be expected to be more frequent than exposure in a commercial agricultural setting. Therefore, this practice would be expected to pose a greater risk of infection. This model practice is designed to describe the application of dried or composted treated sludge that is incorporated into the soil before the crops are planted. The user may specify the proportions of aboveground, on-ground and below-ground crops in the garden.

APPLICATION (1) represents the application of dried or composted sludge to a garden (size given by AREA [P(7)], default 0.015 ha). The pathogen concentration (ASCRS [P(1)], Table A-2) and application rate (APRATE [P(2)], default 25 T/ha) are variables that can be entered by the user of the model. The default method of application is spreading by hand (APMETH [P(6)] = 1).

Because the processed sludge is assumed to be stable, there is no die-off during APPLICATION (1). The entire contents of APPLICATION are transferred to INCORPORATION (2). The default time for transfer from APPLICATION (1) to INCORPORATION (2) is 24 hours.

INCORPORATION (2) involves the mixing, by plowing or cultivation, of the sludge and sludge-associated pathogens evenly throughout the upper 15 cm of soil. Particulate emissions generated by cultivation are represented by a transfer from INCORPORATION (2) to APPLICATION/TILLING EMISSIONS (3*) beginning at hour 24, and extending for enough time to cultivate the field (at a rate of 0.005 ha/hour). At the end of this time, all remaining pathogens are transferred to SOIL SURFACE (4). During incorporation, pathogens will be inactivated at a rate characteristic of the organism in moist soil at the expected soil surface temperature. This temperature is taken to be 5°C above ambient air temperature (TEMP [P(8)]) to allow for surface warming (Brady, 1974; USDA, 1975). INCORPORATION (2) dilutes the pathogens by mixing the sludge with soil; the concentration of pathogens becomes (ASCRS pathogens/kg $*$ APRATE kg/ha)/($2*10^6$ kg/ha).

APPLICATION/TILLING EMISSIONS (3*) is an exposure compartment that receives the dust, or suspended particulates, generated by spreading the composted sludge or by tilling the dried sludge or sludge-soil mixture. Particulates released during APPLICATION (1) are assumed to be undiluted dried sludge, at a concentration equal to that at compost production sites (0.015 g/m^3 (Clark et al., 1983)). Tilling occurs at INCORPORATION (2) and at times specified by TCULT [P(67)]. Additional tilling does not occur if TCULT = -2, but can occur biweekly (TCULT = 0) or at a single time given by TCULT > 0. Particulates released during INCORPORATION (2) are assumed to be undiluted dried sludge whereas, during later cultivations, they comprise a soil-sludge mixture. The concentration of airborne particulates in this compartment is calculated using an equation for dust emissions during cultivation (U.S. EPA, 1985b). The source strength and exposure equations are described in Chapter 5 and in Volume II: User's Manual. This compartment is strictly an exposure compartment, and no die-off of pathogens is assumed other than the die-off rate incorporated in the aerosol subroutines. Exposure calculations are made by Subroutine RISK.

SOIL SURFACE (4) describes the processes occurring in the upper 15 cm of the soil layer. There are no practice-specific differences from the general description above.

WIND-GENERATED PARTICULATES (5*) describes the airborne particulates generated by wind at a user-supplied time TWIND [P(23)] (default 60 hours). Die-off rates are those expected for pathogens in air-dried soil at the ambient temperature. The exposed individual is standing in the garden or at a user-specified distance (default 200 m) downwind from the garden during a windstorm. The wind-generated exposure is calculated from user-specified values for duration (DWIND [P(24)]) and severity (WINDSP [P(25)]) of the windstorm (default values 6 hours at 18 m/sec (40 mph)) assuming, as a worst case, that the fraction of soil surface with plant cover is COVER [P(30)] = 0. Exposure calculations are made by Subroutine RISK.

SURFACE RUNOFF (6*) is not applicable in this practice because runoff is assumed to return to the domestic sewage treatment system without presenting a risk of infection to the user of the sludge.

DIRECT CONTACT (7*) is the exposure compartment for the garden worker or for a child younger than 5 years old who plays in or walks through the garden site, incidentally ingesting 0.1 g of soil and 0.1 g crop surface. This human receptor represents the worst-case example of an individual contacting contaminated soil or soiled clothing or implements. Before all pathogens have been transferred to SOIL SURFACE (4), exposure is at the pathogen concentration found in undiluted sludge whereas, after the transfer, the concentration is that calculated for the soil-sludge mixture. Exposure calculations are made by Subroutine RISK.

SUBSURFACE SOIL (8) describes the processes and transfers for pathogens in the subsurface soil between 15 cm depth and the water table. Pathogens are transferred from SOIL SURFACE (4) by leaching after rain or irrigation. The fraction of pathogens transferred is a user-supplied value (SUBSOL [P(44)], default pathogen-specific (Table A-2)). Die-off rates are characteristic of pathogens in soil at the ambient temperature.

GROUNDWATER (9) is not applicable in this practice because no provision is made for subsequent exposure to pathogens carried by groundwater. It is assumed that GROUNDWATER is not used for either irrigation or drinking water.

IRRIGATION WATER (10) is not applicable in this practice because irrigation water is assumed to come from an uncontaminated domestic water supply.

SOIL SURFACE WATER (11) is the compartment serving as a source of pathogens for SOIL SURFACE (4) and for CROP SURFACE (14). It describes the suspension of crop- and soil-associated pathogens, as well as those transferred by irrigation, in the layer of water resulting from irrigation or rainfall. It also describes their transfer back to either SOIL SURFACE or CROP SURFACE. The residence time for pathogens in this compartment is determined by the depth of water and by the infiltration rate. The process functions are those associated with other water compartments.

OFFSITE WELL (12*) is not applicable in this practice.

IRRIGATION AEROSOLS (13*) is not applicable in this practice.

CROP SURFACE (14) describes contamination of vegetable crops by transfer of pathogens from SOIL SURFACE (4) or SOIL SURFACE WATER (11). No transfers to CROP SURFACE occur before TCROP [P(68)], the time at which the plants have emerged (default 720 hours). Vegetables can be grown aboveground, on-ground or below-ground. These are represented by tomatoes, zucchini and carrots, respectively. Process functions are assumed to be influenced by drying, thermal inactivation and solar radiation and are thus characteristic of pathogens in surface soil (5°C above ambient temperature).

HARVESTING (15) occurs at THARV [P(69)] (default 1680 hours). At this time, all pathogens remaining in CROP SURFACE (14) are transferred to HARVESTING (15). The same process functions apply as in CROP SURFACE (14). The crop is held for 24 hours before being processed. The number of pathogens is then transferred to CROP (16*).

CROP (16*) is the compartment in which further processing takes place. The number of pathogens/crop unit is calculated in this compartment and is the figure used by the vegetable-exposure risk calculation.

A 24-hour pathogen exposure is computed by Subroutine VEG. Pathogen concentrations are determined as number/crop unit.

Before being consumed, vegetables normally are processed in some way. Included in the program is a series of user-selectable processing steps. The user has the option of choosing any or all processing steps and of specifying some conditions within processing steps. In the default condition, the human receptor consumes minimally prepared vegetables (washed, but not peeled or cooked) at a rate of 81 g tomatoes, 80 g zucchini or 43 g carrots per eating occasion (Pao et al., 1982).

3.7. APPLICATION OF DRIED OR COMPOSTED SLUDGE TO RESIDENTIAL LAWNS (PRACTICE V)

Dried or composted treated sludge may be available to the public as a bulk or bagged product for use as fertilizer or soil conditioner in the preparation of seed beds for domestic lawns. Although some studies have shown that composting is highly effective in removing pathogens from sludge (Wiley and Westerberg, 1969), other studies have shown that bacterial pathogens may grow in dried or composted sludge to concentrations of $1*10^6$ organisms/kg dry weight (U.S. EPA, 1988). Individuals engaged in preparing a seed bed for a lawn are likely to come into contact with the soil and any additives used to improve the seed bed. If the soil or the additives contain pathogens, this practice would be expected to pose a risk of infection. This model practice is designed to describe the application of dried or composted treated sludge that is incorporated into the soil before the lawn is seeded.

APPLICATION (1) represents the application of dried or composted sludge to a lawn (size given by AREA [P(7)], default 0.05 ha). The pathogen concentration (ASCRS [P(1)], Table A-2) and application rate (APRATE [P(2)], default 25 T/ha) are variables that can be entered by the user of the model. The default method of application is spreading by hand (APMETH [P(6)] = 1).

Because the processed sludge is assumed to be stable, there is no die-off during

APPLICATION (1). The entire contents of APPLICATION are transferred to INCORPORATION (2). The default time for transfer from APPLICATION to INCORPORATION is 24 hours.

INCORPORATION (2) involves the mixing, by plowing or cultivation, of the sludge and sludge-associated pathogens evenly throughout the upper 15 cm of soil. Particulate emissions generated by cultivation are represented by a transfer from INCORPORATION to APPLICATION/TILLING EMISSIONS (3*) beginning at hour 24 and extending for enough time to cultivate the field. At the end of this time, all remaining pathogens are transferred to SOIL SURFACE (4). During incorporation, pathogens will be inactivated at a rate characteristic of the organism in moist soil at the expected soil surface temperature. This temperature is taken to be 5°C above ambient air temperature (TEMP [P(8)]) to allow for surface warming (Brady, 1974; USDA, 1975). INCORPORATION (2) dilutes the pathogens by mixing the sludge with soil; the concentration of pathogens becomes (ASCRS pathogens/kg $*$ APRATE kg/ha)/($2*10^6$ kg/ha).

APPLICATION/TILLING EMISSIONS (3*) is an exposure compartment that receives the dust, or suspended particulates, generated by tilling the dried sludge or sludge-soil mixture. Particulates released during APPLICATION (1) are assumed to be undiluted dried sludge at a concentration equal to that at compost production sites (0.015 g/m^3 (Clark et al., 1983)). Tilling occurs at INCORPORATION (2) and at times specified by TCULT [P(67)]. Additional tilling does not occur if TCULT = -2, but can occur biweekly (TCULT = 0) or at a single time given by TCULT > 0. Particulates released during INCORPORATION (2) are assumed to be undiluted dried sludge whereas, during later cultivations, they comprise a soil-sludge mixture. The concentration of airborne particulates in this compartment is calculated using an equation for dust emissions during cultivation (U.S. EPA, 1985b). The source strength and exposure equations are described in Chapter 5 and in Volume II: User's Manual. The compartment is strictly an exposure compartment, and no die-off of pathogens is assumed other than die-off rates incorporated in the aerosol subroutines. Exposure calculations are made by Subroutine RISK.

SOIL SURFACE (4) describes the processes occurring in the upper 15 cm of the soil layer. There are no practice-specific differences from the general description above.

WIND-GENERATED PARTICULATES (5*) describes the airborne particulates generated by wind at a user-supplied time TWIND [P(23)] (default 60 hours). Die-off rates are those expected for pathogens in air-dried soil at the ambient temperature. The exposed individual is standing on the lawn or at a user-specified distance (default

200 m) downwind from the lawn during a windstorm. The wind-generated exposure is calculated from user-specified values for duration (DWIND [P(24)]) and severity (WINDSP [P(25)]) of the windstorm (default values 6 hours at 18 m/sec (40 mph)) assuming, as a worst case, that the fraction of soil surface with plant cover is COVER [P(30)] = 0. Exposure calculations are made by Subroutine RISK.

SURFACE RUNOFF (6*) is not applicable in this practice, because runoff is assumed to return to the domestic sewage treatment system without presenting a risk of infection to the user of the sludge.

DIRECT CONTACT (7*) is the exposure compartment for the lawn worker or for a child younger than 5 years old who plays in or walks through the lawn site, incidentally ingesting soil or crop surface. This human receptor represents the worst-case example of an individual contacting contaminated soil, soiled clothing or implements. Before all pathogens have been transferred to SOIL SURFACE (4), exposure is at the pathogen concentration found in undiluted sludge whereas, after the transfer, the concentration is that calculated for the soil-sludge mixture.

After 840 hours, the time assumed necessary for the lawn to require mowing, the lawn is mowed weekly, and a fraction, 0.1, (DRECTC, Variable 5 of the Subroutine RISK variables) of the pathogens associated with CROP SURFACE (14) is transferred to DIRECT CONTACT. It is assumed that the person mowing the lawn is exposed by inhalation and subsequent ingestion to 0.1 g of CROP SURFACE (14) at each mowing. Exposure calculations are made by Subroutine RISK.

SUBSURFACE SOIL (8) describes the processes and transfers for pathogens in the subsurface soil between 15 cm depth and the water table. Pathogens are transferred from SOIL SURFACE by leaching after rain or irrigation. The fraction of pathogens transferred is a user-supplied value (SUBSOL [P(44)], default pathogen-specific (Table A-2). Die-off rates are characteristic of pathogens in soil at the ambient temperature.

GROUNDWATER (9) is not applicable in this practice because no provision is made for subsequent exposure to pathogens carried by groundwater. The model assumes that GROUNDWATER is not used for either irrigation or drinking water in this practice.

IRRIGATION WATER (10) is not applicable in this practice because irrigation water is assumed to come from a non-contaminated domestic water supply.

SOIL SURFACE WATER (11) is the compartment serving as a source of pathogens for SOIL SURFACE (4) and for CROP SURFACE (14). It describes the suspension of crop- and soil-associated pathogens, as well as those transferred by irrigation, in the layer of water resulting from irrigation or rainfall. It also describes their transfer back to either SOIL SURFACE (4) or CROP SURFACE (14). The residence time for pathogens in this compartment is determined by the depth of water and by the infiltration rate. The process functions are those associated with other water compartments.

OFFSITE WELL (12*) is not applicable in this practice.

IRRIGATION AEROSOLS (13*) is not applicable in this practice.

CROP SURFACE (14) describes the transfer of pathogens from SOIL SURFACE (4) and SOIL SURFACE WATER (11) to the mowed or cut grass. The model assumes that, as the grass emerges (default TCROP [P(68)] = 240 hours), it takes with it a fraction (SSTCS [P(57)], default $1 \cdot 10^5$) of the SOIL SURFACE (4) pathogens. Thereafter, the same transfer occurs daily. There is also a daily transfer back to SOIL SURFACE (CSTSS [P(56)], default 0.1) and transfers to DIRECT CONTACT (7*) (PSTMG [P(55)], default 0.5). Process functions are assumed to be influenced by drying, thermal inactivation and solar radiation and are thus characteristic of pathogens in surface soil (5°C above ambient temperature).

HARVESTING (15) is not applicable in this practice. Exposure to CROP SURFACE (14) as a result of mowing is modeled by routines incorporated into CROP SURFACE (14) and DIRECT CONTACT (7*).

CROP (16*) is not applicable in this practice.

4. EXPOSURE PATHWAYS TO HUMAN RECEPTORS

Sludge applied to land surfaces can give rise to human infection through the following pathways:

- Ingestion of soil or sludge;
- Inhalation of aerosols;
- Leaching of pathogens from land application sites to surface water and groundwater, and subsequent ingestion;
- Transfer of pathogens to vegetation or food crops, and subsequent ingestion; and
- Transfer from soil, water or vegetation to animals by contact or ingestion and subsequently, transfer to humans.

Human ingestion of sludge, contaminated soil, contaminated crop surface, groundwater, surface water or foodstuffs is considered to be the major source of risk for infection associated with land disposal of sludge. Contact with and ingestion of contaminated water and sediments through swimming activities are also considered as a risk to the human receptor. The significant exposure compartments in each sludge management practice, indicated with an asterisk in Table 3-2, are pathways for which exposure calculations are performed by this model.

Although it is possible that many individuals may be exposed to some extent to sludge-borne contaminants, it is common practice to model a hypothetical individual whose activities lead to a maximal reasonable exposure to the hazard. The risk of adverse consequences to this individual is determined, and, if the calculated risk is acceptable, then the risk to other persons should be negligible. This model sums the hourly exposure of a human receptor to pathogens in each exposure compartment and computes the daily (24-hour) probability of the individual receiving an exposure exceeding an infective dose. The model assumes no cumulative effects beyond one day and no interaction among pathogens or between the pathogen of interest and components of the matrix in which it occurs.

The degree of exposure is determined by the number of sludge pathogens ingested during the relevant time period. This number is determined by the concentration of pathogens in the consumed materials (determined in each exposure compartment; Appendix A, Table A-3 lists some proposed initial values for the pathogen concentration parameter, ASCRS) multiplied by the volume or mass of material consumed. Although the quantity of potentially contaminated food, water or air consumed can be extremely variable, some typical values are assumed. Much of the material in this chapter describing the assumptions and calculations used for estimating human exposures is taken from the earlier version of the model (U.S. EPA, 1980). Several user-supplied parameters are available to change the conditions of human exposure to the pathogens. During the input phase of running the computer model, the user has the opportunity to change these values from the default values. These infection risk parameters, together with their default values and definitions, are listed in Appendix A, Table A-4.

4.1. EMISSIONS FOLLOWING APPLICATION/INCORPORATION

Particulates, defined here as airborne dust or droplets, are generated by many of the activities modeled in the sludge management practices, such as irrigation, tilling of the soil or wind erosion. This material and the pathogens associated with it might be inhaled by people living and working near sludge application sites. Because of the decay of viable pathogens after incorporation into soil, the maximal exposure to application aerosols would be expected to occur at the time of application when liquid sludge is sprayed on the field or dried sludge is tilled into the soil. While it is more likely that viruses or bacteria will be found in aerosols than the heavier ova and cysts of parasites, each pathogen is treated in the same manner. Ova and cysts may settle out from aerosols more rapidly than viruses and bacteria, but they can be resuspended by winds.

Aerosols are generated during the dumping and spreading of sludge. No data are available on the generation and transport of aerosols emanating from the dumping process. However, other data indicate that microorganisms may be transported substantial distances by winds acting on aerosols from waves on large bodies of water and that pathogens may be concentrated by evaporation during aerosol formation (U.S. EPA, 1986). In the case of spray application of liquid sludge, a calculation is done for onsite exposure to aerosols, but the model assumes that workers will not intentionally be exposed to the direct spray. A separate calculation is done in which the human receptor is assumed to be an offsite person at some distance from the aerosol source. The distance can be specified by the user, or the default value of 200 m can be used.

APPLICATION/TILLING EMISSIONS (3*) are generated by tilling the sludge into the soil or by cultivating crops. The dust generated during cultivation is assumed to settle rapidly and thus would not constitute an offsite exposure. In this case, the human receptor is assumed to be the operator of a tractor or garden tiller in the application area. The amount of dust generated by cultivation is calculated during

INCORPORATION (2) and at TCULT [P(67)], beginning at hour 1 (for worst case) for dried/composted sludge and after 24 hours (to allow the field to dry) following application of liquid sludge. The calculation computes the transfer from INCORPORATION (2) or SOIL SURFACE (4) to APPLICATION/TILLING EMISSIONS (3*). For all practices, the calculation is done once for each hour of tilling. In Practices I through III, tilling time is AREA/5, where AREA is the area of the field in hectares, assuming that one tractor operator will till 40 ha in an 8-hour day. For Practices IV and V, the tilling rate is assumed to be 0.005 ha/hour, and the time of tilling is AREA/0.005 hour.

In Practices I through III, the dust cloud is assumed to contain particles at a concentration calculated by equations for generation of dust by mechanical disturbance of dry soil (U.S. EPA, 1983a). For Practices IV and V, the concentration of particulates is assumed to be 15 mg/m^3. Although dust concentrations during application of dried sludge are not available, the value of 15 mg/m^3 is similar to concentrations detected at compost preparation sites (Clark et al., 1983). This material is assumed to form a short-lived cloud, exposing the operator of tilling equipment but not escaping from the site. The volume of the cloud is defined by the area of application and a height (HT [P(33)]) set to a default value of 1.6 m. The human receptor is assumed to be located in the center of the particulate cloud, although in reality the cloud would immediately drift downwind from the point of generation.

4.2. PARTICULATES FROM SOIL SURFACE

WIND-GENERATED PARTICULATES (5) are released from the soil surface when soil particles are loosened and entrained by the wind, a process known as wind erosion. For wind erosion to occur, the surface must be dry and free of cover that can absorb the wind stress necessary to suspend particles. In Practices II and III, 90% ground cover is taken as the default value, whereas in Practices I, IV and V, a period during which there is no ground cover is assumed to provide the worst case for wind erosion. No particulates are generated if the windstorm coincides with a rainfall or irrigation event. Pathogens on soil particles are assumed to die off at a temperature-dependent rate characteristic of air-dried soil.

Wind erosion during a windstorm of 18 m/s (approximately 40 mph) and 6 hours duration is assumed to result in an offsite exposure to an individual at a default distance of 200 m from a point source representing one hectare. This individual is assumed to inhale airborne particulates at a rate of 20 m^3/day for the duration of the windstorm, and the pathogens are assumed to be swallowed after inhalation.

4.3. SURFACE RUNOFF

SURFACE RUNOFF (6) occurs whenever the amount of water applied to the soil exceeds the retention capacity of the soil. The retention capacity varies with soil type, cover characteristics, land use practices and hydrologic condition. The source of water for runoff is limited to rainfall, because irrigation is expected to be controlled so that runoff is minimal. As a result of surface runoff, some of the surface soil is washed from the site. The extent of sediment transport depends on the intensity of rainfall, the inherent erodibility of the soil and the contour and use of the land. This model includes a subroutine to calculate the amounts of runoff and sediment transport associated with each rainfall event. A detailed description of this subroutine is given in Volume II: User's Manual.

Some soil surface microbes are expected to be suspended in runoff water and will be removed from the site in association with sediment particles. The model assumes that sediment transported from the field is representative of the soil surface layer, in which pathogen distribution is homogeneous. An onsite pond whose volume is 100 m^3/ha of watershed receives surface runoff and sediment. This pond is not expected to be used as a water source for spray irrigation, because irrigation at the rate of 5 cm/day twice weekly requires 1000 m^3/ha of water each week.

The pond is considered to be a potential exposure compartment, when the human receptor incidentally ingests water while swimming. Subroutine SWIMER computes the daily pathogen exposure for the swimmer. The model assumes ingestion of 100 mL of pond water (Pipes, 1978) on any given day (or 0.004167 L/hour for 24 hours). Because the use of a runoff pond for drinking water is unlikely and because extensive dilution of the runoff would occur in other receiving bodies, the pond swimmer is assumed to represent a worst-case exposure.

4.4. DIRECT CONTACT

4.4.1. Direct Removal. DIRECT CONTACT (7*) occurs when surface soil is transported offsite either intentionally or casually by people. The amount of soil removed has a negligible effect on the pathogen content of the SOIL SURFACE (4) compartment, but small amounts of highly contaminated soil may represent a significant exposure to sensitive human receptors. Surface soil, defined as the upper 15 cm (or 5 cm, depending on practice) of soil at the application site, is assumed to be in the vadose (unsaturated) zone. Exposure due to inadvertent ingestion of surface soil is determined by the pathogen concentration in this material (number/g) multiplied by the mass ingested (a user-supplied parameter, DRECTS (Variable 6 in Subroutine RISK), default 0.1 g/day). Separate direct exposures to SOIL SURFACE (4), SUBSURFACE SOIL (8) and MANURE (19) (onsite and offsite) are not included. Typical daily consumption of dust and dirt has been estimated as approximately 0.02 g for adults (U.S. EPA, 1984), but it seems reasonable to assume that a field worker may ingest larger quantities. Calculated rates of soil ingestion among children vary, with typical mean values near 0.1 g/day (Binder et al., 1986). These ingestion estimates depend on measurements of soil metals, and do not include corrections for quantities of these metals in foods, resulting in overestimates by a factor of 2-6 (Calabrese, 1988). The 95th percentile value reported by Binder et al. (1986) was 0.4-0.6 g/day before correction for food. For this model, the default value for all soil ingestion compartments taken together is 0.1 g soil/day for Practice I and other agricultural practices (a value which is 5 times the estimated value for adults (U.S. EPA, 1984)). For Practice I and other agricultural practices, the human receptor is assumed to be a child younger than 5 years old or a field worker who casually ingests contaminated soil from the field. In contrast, for D&M practices the human receptor is a child or worker who ingests unincorporated sludge or compost.

4.4.2. Crop Surface. Plants growing in sludge-amended soil may be contaminated by sludge-borne pathogens. Incidental contact with and handling of leaves, stems or fruits may result in ingestion and consequent infection. In this model, the amount of CROP SURFACE (14) is given by the variable HAY [P(73)] (default 1.6 kg/m^2). Each day the human receptor casually ingests the crop surface pathogens contained in an amount of CROP SURFACE given by DRECTC (Variable 5 in Subroutine RISK), default 0.1 g.

4.4.3. Mowed Grass. Grass fertilized by composted sludge in D&M practices may be contaminated with pathogens in the sludge. Direct skin contact with contaminated grass is not considered to be a significant exposure hazard, but removal of grass from the site after it is cut represents a potential for incidental contact and subsequent ingestion. The exposure calculation assumes that the daily ingestion of cut grass (DRECTC, Variable 5 in Subroutine RISK) is, as a worst case, equivalent to the incidental ingestion of soil (0.1 g).

4.5. GROUNDWATER AT AN OFFSITE WELL

GROUNDWATER (9) represents the aqueous component of the saturated zone.

Microbes are assumed to be leached to GROUNDWATER from SOIL SURFACE (4) via infiltration of rainwater and irrigation water through SUBSURFACE SOIL (8). However, quantitative models to describe this leaching have not been developed; as an approximation, a fraction of the pathogens in SOIL SURFACE (4) is designated as transferred to SUBSURFACE SOIL (8). This fraction, variable SUBSOL [P(44)], is a judgment estimate, and the user is encouraged to refine it as better information becomes available.

Groundwater may be transported from the field to household wells, OFFSITE WELL (12*), for domestic use Transport of pathogens from SOIL SURFACE (4) to an OFFSITE WELL (12*) requires movement of the organisms through the vadose SUBSURFACE SOIL (8), then through saturated soil to the well. The rates of inactivation and decay of pathogens are assumed to be different in the saturated zone from those characteristic of the vadose zone. In most cases, microbes survive much longer in groundwater than in soil. Microbes reaching the groundwater are assumed to be uniformly mixed in an aquifer whose thickness (AQUIFR [P(9)] and porosity (POROS [P(10)] can be specified by the user. The transport subroutine is called after a rainfall or irrigation event that allows for leaching of microbes into the groundwater. It then computes the average daily pathogen concentration at an offsite well at a user-specified distance from the field (default 50 m). The human receptor is an individual drinking 2 L of untreated water daily from the offsite well.

4.6. FUGITIVE EMISSIONS (AEROSOLS) FROM IRRIGATION

The source of water for irrigation may be either an onsite well receiving water from GROUNDWATER (9) or a source of treated liquid sludge (if spray application is chosen for Practices II and III). The volume and frequency of irrigation required for a given agricultural practice depend on a number of variables including crop, soil type and weather conditions. Irrigation water can be applied as a spray or through ditches or pipes that are on or in the ground. In this model, however, spray irrigation is assumed to provide a worst-case exposure to pathogens. IRRIGATION AEROSOLS (13*) are generated during spraying operations and by wind activity on waters receiving sludge or sludge-contaminated runoff water. Exposure calculations assume a delivery rate of 0.5 cm/hour for spray irrigation, with a default total amount of 10 cm (5 cm twice weekly). The rate of irrigation is assumed to be controlled so that no surface runoff occurs.

If the source of irrigation water is contaminated with sludge pathogens, spray irrigation would be expected to cause contamination of aboveground crop surfaces. On the other hand, infiltration via ditches would not contaminate aboveground crops and would not add significantly to contamination of below-ground crops. The variable DRECTC (Variable 5 in Subroutine RISK), which describes incidental ingestion of CROP SURFACE (14), is used when CROP SURFACE is contaminated by irrigation.

Spray irrigation must be considered a significant aerosol source for offsite exposure of an individual who breathes the airborne pathogens downwind from the field during the lifetime of the irrigation-generated aerosol. This exposure is calculated in IRRIGATION AEROSOLS (13*) by a Gaussian-plume model which is called during irrigation. The calculated exposure to airborne pathogens includes all particle sizes. However, particles less than 2 microns in diameter are likely to be inhaled, whereas larger particles are more likely to be swept out of the respiratory tract and swallowed (Adams and Spendlove, 1970; Fuchs, 1964; Sorber and Guter, 1975). Most sludge-borne pathogens would be expected to have different infectivities upon inhalation as compared to ingestion, thereby making predictions of probability of infection difficult. Inhalation is assumed to be equivalent to ingestion as a route of infection.

4.7. CROPS/PRODUCTS

4.7.1. Vegetable Crops. Edible crops represent the major product of Practices I and IV, which end with the harvest of vegetable crops. The number of pathogens/crop unit is calculated in the final compartment of each of these sludge management practices and is the value used by the vegetable-exposure risk calculation. Crops produced in sludge-amended fields may be contaminated by pathogens in soil on the CROP SURFACE (14). The amount of soil associated with each crop unit may be specified by the user. Transport of human pathogens into crop tissue is assumed not to be significant.

A full 24-hour pathogen exposure rather than a 1-hour exposure is computed by Subroutine VEG because this subroutine is called only once. Vegetables can be grown above ground, on ground or below ground. These are represented by tomatoes, zucchini and carrots, respectively. Pathogen concentrations are determined as number/crop unit. A crop unit is the average weight of each individual vegetable (tomato = 0.23 kg, zucchini = 0.23 kg, carrot = 0.10 kg). Daily consumption is also averaged as 81 g, 80 g and 23 g for these vegetables, respectively (Pao et al., 1982).

Practice I specifies that sludge is incorporated before the crop is planted. Therefore, the minimum time from APPLICATION (1) to HARVEST (15) is the published time required for maturation of the crop in question. This value is a variable that can be supplied by the user (TCROP [P(68)]).

Before being consumed, vegetables are normally processed in some way. Included in the program is a series of user-selectable processing steps that are outlined below. The user has the option of choosing any or all processing steps and of specifying some conditions within processing steps. The parameters that control processing are listed in Table A-4.

Processing steps are modeled to account for removal or inactivation of pathogens by washing, blanching, etc., but for a worst-case analysis, the model assumes that no processing of the crop occurs other than washing. Thus, the human receptor in Practice I or IV is an individual who eats one standard serving of the minimally prepared crop (washed, but not peeled or cooked). Vegetables are usually washed before being commercially processed or before being cooked or eaten raw in the home. Both types of washing are designed to remove visible dirt and will also remove 90% of the pathogens clinging to fresh vegetables (Hersom and Hulland, 1964). Selecting the washing step by setting IWASH=1 leads to a 90% reduction in pathogens associated with the vegetables being processed.

4.7.2. Pasture Crops. Contaminated pasture crops may serve as a source of infection of cattle being grazed on the pasture. Infection of cattle is modeled if the daily amount of ANIMAL CONSUMPTION (17) is $>10^8$ Salmonella. Ascaris and enterovirus are assumed not to infect cattle. If infected cattle remain in the same field, the pathogen load in accumulated manure might add significantly to the pathogen population. The model assumes that there is a user-defined distribution (TMTSS [P(61)]) of manure between SOIL SURFACE (4) and CROP SURFACE (14). Default values are set at 70% and 30%, i.e., 70% of pathogens from the manure of infected cattle reach SOIL SURFACE (4) and 30% remain on CROP SURFACE (14). This compartment does not represent a direct exposure for a human receptor.

4.7.3. Processed Animal Feed. This compartment represents an exposure to cattle by ingestion of processed feed contaminated with soil and sludge. As discussed in the description of Practices II and III, cattle must ingest at least 10^8 bacteria to initiate an enteric infection. Following infection, each cow excretes 4 kg DW of manure daily at an arbitrary concentration of 10^9 organisms/kg for 4 days. This contaminated MANURE (19) can contaminate HIDE (21) and UDDER (22), but it does not contaminate CROP SURFACE (14) because, in this case, crops have already been harvested and processed. This compartment does not represent a direct exposure to a human receptor.

4.7.4. Manure. This compartment is intended to describe the transfer of pathogens from infected cattle to HIDE (21) and UDDER (22), as well as the additional pathogen load to surface soil resulting from cattle-raising activities on sludge-amended pasture land. Because of the acidity of the cattle rumen, pathogens in contaminated soil ingested with forage are unlikely to survive to initiate an enteric infection. The model assumes that an infective dose of 10^8 bacteria or enteroviruses per day is required to establish an infection. After infection, the pathogen load associated with MANURE (19) is calculated, assuming production of 4 kg/day DW of manure and a pathogen concentration of 10^9 organisms/g for 4 days. Of these, the fraction 0.001 is assumed to remain on the animal's hide and the fraction 0.001 on the udder.

4.7.5. Meat. Pathogen exposure through meat consumption occurs when the beef cattle option is selected in Practice II or Practice III. This exposure risk calculation is performed on the pathogen population transferred to MEAT (18*) at the time of slaughter. The human receptor is assumed to consume 0.256 kg/day of meat (U.S. FDA, 1978).

When a cow is slaughtered, the carcass is washed with a solution of hot water and chlorine, covered with a shroud and cooled to 0°C (Fields, 1979). The effects of this treatment on meat-associated pathogens are not included in either sludge management practice process functions or in the exposure risk calculations. Treatment after slaughter is designed to reduce surface contamination, which is generally the only pathogen contamination associated with beef production. The model does not attempt to estimate the area of carcass contaminated and the area consumed by the eater but treats pathogens associated with meat as if they are spread evenly throughout the product rather than concentrated on the outside and cut surfaces.

Although contaminated meat, poultry and eggs are the major source of human salmonellosis, most of the contamination is attributable to endemic levels of Salmonella in the flocks and herds. Contamination of meat by ingested sludge-borne enteroviruses and bacteria is not expected to be a significant exposure route for humans, assuming that only healthy animals are slaughtered and that good sanitary practices are carried out during meat processing. Meat containing encysted reproductive forms of tapeworms and other helminths is a significant route of infestation of humans. However, with the exception of the beef tapeworm, Taenia saginata (Kowal, 1985), the transfer of parasites from domestic sewage to cattle is not likely, because cattle are not susceptible to the parasites found with significant frequency in domestic sewage.

The model assumes that if an animal is infected with Salmonella or an enterovirus, a small fraction (0.001) of the pathogens from MANURE (19) are transferred daily to HIDE (21). In turn, a fraction of HIDE pathogens is transferred to MEAT (18) at the time of slaughter. The default value for this fraction is 0.1 times the number of pathogens in HIDE, distributed over 270 kg of meat per animal.

4.7.6. Milk. Pathogen exposure through milk consumption occurs when the dairy cow option is selected in Practice II or Practice III. The default condition models the consumption of raw milk which has been stored for 24 hours. This condition gives a worst-case probability of infection.

According to the model's assumptions, each cow delivers 15 L of milk per day. The pathogen load transferred to MILK (20*) is distributed evenly throughout the entire quantity of milk collected from the dairy herd. Twelve cows constitute the herd in Practices II and III when default values are used. The quantity of milk being considered is, therefore, 180 L per day. Milk from each milking is kept separate. Process functions act upon milk-associated pathogens during an assumed 24 hours between milking and consumption. (This time was chosen to simulate the home consumption of raw milk. Although commercially produced milk is stored longer before consumption, it is produced under conditions which preclude the presence and growth of pathogens.) The user may specify both the duration and temperature of raw milk storage. Default values are 24 hours for TMIS2 and 4°C for TEMI2 (Variables 24 and 20, respectively, in Subroutine RISK, Table A-4).

Unless the cow is infected with a pathogen and develops a septicemia, presence of the pathogen within the cow's tissues does not occur. Transfer of Salmonella and other bacterial pathogens from the blood of a bacteremic cow to milk is highly unlikely and is not included as part of this model. Good sanitation practices in the milking barn, effective pasteurization, and compliance with health regulations forbidding sale of milk containing viable Salmonella are assumed to minimize any risk to the public from sludge-borne pathogenic contaminants in milk. Therefore, the default value for transfer of pathogens to MILK (20) from MANURE (19) or contaminated SURFACE SOIL (4) is zero. However, by specifying a fraction of pathogens (UTM [P(65)]) on the udder surface (UDDER (22)) to be transferred to MILK (20*) at the time of milking, the user can simulate the production of contaminated milk. In this case the human receptor would be assumed to drink the milk without pasteurization.

Pathogen exposure is computed by Subroutine MILK, which uses the concentration of pathogens in MILK (20*) and a daily consumption figure. The human receptor is assumed to drink 2 kg milk/day, roughly three times the national average daily milk consumption of 0.756 kg (U.S. FDA, 1978).

5. MODEL DESCRIPTION AND EXAMPLE CALCULATIONS FOR EXPOSURE PATHWAYS

The model uses an approach in which each compartment represents a discrete point in a treatment or application pathway where pathogen populations are computed as a function of time. Within each compartment (n), the number of organisms may increase or decrease, as described by a rate parameter (RHOn), and transfer functions (TRxy) describe the movement of organisms into or out of each compartment. Transfer functions are denoted by indicating first the number of the compartment from which the transfer is made (i.e., the donor compartment) and then the number of the receptor compartment. Thus a transfer from Compartment 1 to Compartment 2 would be designated TR12.

The model is designed to calculate the concentration of the chosen organism in each compartment at a number of 1-hour time increments. Within each compartment, the population of organisms increases or decreases in number at an exponential rate.

The model includes a set of default values for each rate parameter and initial concentration to be used in the calculations, and the user has the option of substituting other values, corresponding to, for example, different organisms, different treatment conditions or different values of soil temperature, moisture or pH. It contains, therefore, a great deal of built-in flexibility in generating comparative data on pathogen concentrations in various exposure pathways. The endpoint of each release pathway calculation is the number of organisms present in each compartment of the pathway at any given time.

Values were taken from the literature for inactivation rates for Salmonella, Ascaris and enterovirus under a variety of conditions corresponding as closely as possible to the compartments in question. Thus, exponential inactivation of bacteria and enteroviruses in soil or groundwater, or on food exposed to freezing or cooking temperatures, is assumed, whereas bacterial growth is expected in food at moderate temperatures. SLOPE and NTRCPT variables ([P(37)] - [P(40)]) were determined for a least-mean-squares line fitted to a log transform of inactivation rates under different conditions (double log transform for viruses). For a more detailed discussion, see Volume II: User's Manual.

Transfer functions characterizing movement from compartment to compartment may be linear with time or exponentially or proportionally related to the concentration of organisms in the source and destination compartments. Calculations for each compartment of the model option chosen yield the concentration of the selected pathogen in each compartment. To simplify calculations of discrete, presumably instantaneous events superimposed on continuous functions for growth, inactivation and transfer of pathogens, the exponential functions are converted to linear hourly approximations. Thus an inactivation rate of 1.2 logs per day means that the number of organisms remaining after one day will be $N = N_o \bullet 10^{-1.2}$, but after one hour, $N = N_o \bullet 10^{-0.05} = 0.89 \bullet N_o$. The hourly inactivation factor is summed with all transfer factors for the compartment and multiplied by the population of the compartment. This calculation is made once for each hour.

The concentration of pathogens in environmental media (pathogens per kilogram of material) is calculated by dividing the number of pathogens in the selected compartment, N(i), by the weight or volume of material in that compartment. The weight or volume of material in each compartment for which a residue-exposure risk calculation is made is stored in the program. In some compartments the amount of material is controlled by a variable. For example, the user can supply the quantity of water in the groundwater aquifer by specifying the value of AQUIFR [P(9)] and POROS [P(10)]. In other compartments the weight is constant.

Soil is assumed to have an average density of 1.33 g/cm^3. The weight of soil per hectare in a SOIL SURFACE (4) compartment in Sludge Management Practices I, IV and V is $2 \bullet 10^6$ kg (1 ha • 15 cm deep • 1.33 g/cm^3). In Practices II and III, the weight of soil per hectare is $0.667 \bullet 10^6$ kg (1 ha • 5 cm • 1.33 g/cm^3). The concentration of pathogens is calculated by dividing the contents of the relevant compartment by the weight of soil in the compartment.

Exposure estimates, calculated as exposure amount x concentration of pathogen, are made for each exposure compartment. For compartments characterized by a given dose/day, the dose is converted to dose/hour, and the exposure is summed over 24 hours. For example, to simulate ingestion of soil at the daily geometric mean pathogen survival, the daily exposure (default 0.1 g from soil and 0.1 g from crop surface in Practices II and III) is divided by 24, and the exposure estimate is done once for each hour for 24 hours. This is equivalent to using the geometric mean pathogen concentration in the exposure calculation. For exposures with a defined lifetime (one or more hours, or the modeled lifetime of an aerosol, or an operation carried out as part of the use practice), the hourly exposure is summed over the relevant time period.

The risk of infection is determined using MID values from published literature to calculate the probability that the dose to the human receptor will reach or exceed that value. Since the pathogens are assumed to be distributed randomly in the exposure medium, these probabilities are described by a Poisson distribution. Thus a daily ingestion of 0.1 g of soil containing an average of 1 pathogen per gram yields a risk estimate of 0.095 if the MID is 1, but $2 * 10^{-16}$ if the MID is 10. Figure 5-1 shows the calculated probability of infection as a function of average dose for several values of MID.

5.1. EMISSIONS FOLLOWING APPLICATION/INCORPORATION

Application of liquid sludge by spread-flow or injection practices is assumed not to result in the generation of offsite emissions. Spray application of liquid sludge is modeled as generating aerosols that may be transported offsite by a wind whose speed can be chosen by the user (default value is 4 m/s). For the spray option, an application rate of 0.5 cm/hour is assumed, as in the case of irrigation. Details of the method of calculation and sample results are given below in the discussion of particulates.

Particulate emissions resulting from spreading and tilling liquid sludge in Practice I are assumed to be similar to emissions for other agricultural tilling (using a disc, land plane or sweep plow), as described by U.S. EPA (1983a). This calculation is performed beginning at 24 hours to compute the transfer from INCORPORATION (2) to APPLICATION/INCORPORATION EMISSIONS (3*). In Practice I, the calculation is done once for each hour up to AREA/5, where AREA is the area of the field in hectares, assuming that one tractor operator will till 40 ha in an 8-hour day. In Practices IV and V, the length of time is AREA/0.005. The quantity of dust generated by tilling is empirically described as:

$$E = 6.04 * k * s^{0.6} \tag{5-1}$$

where:

E = emission factor (kg/ha)

k = particle size multiplier (dimensionless)

s = fractional silt content of soil.

EFFECT OF INFECTIVE DOSE (MID) ON PROBABILITY OF INFECTION

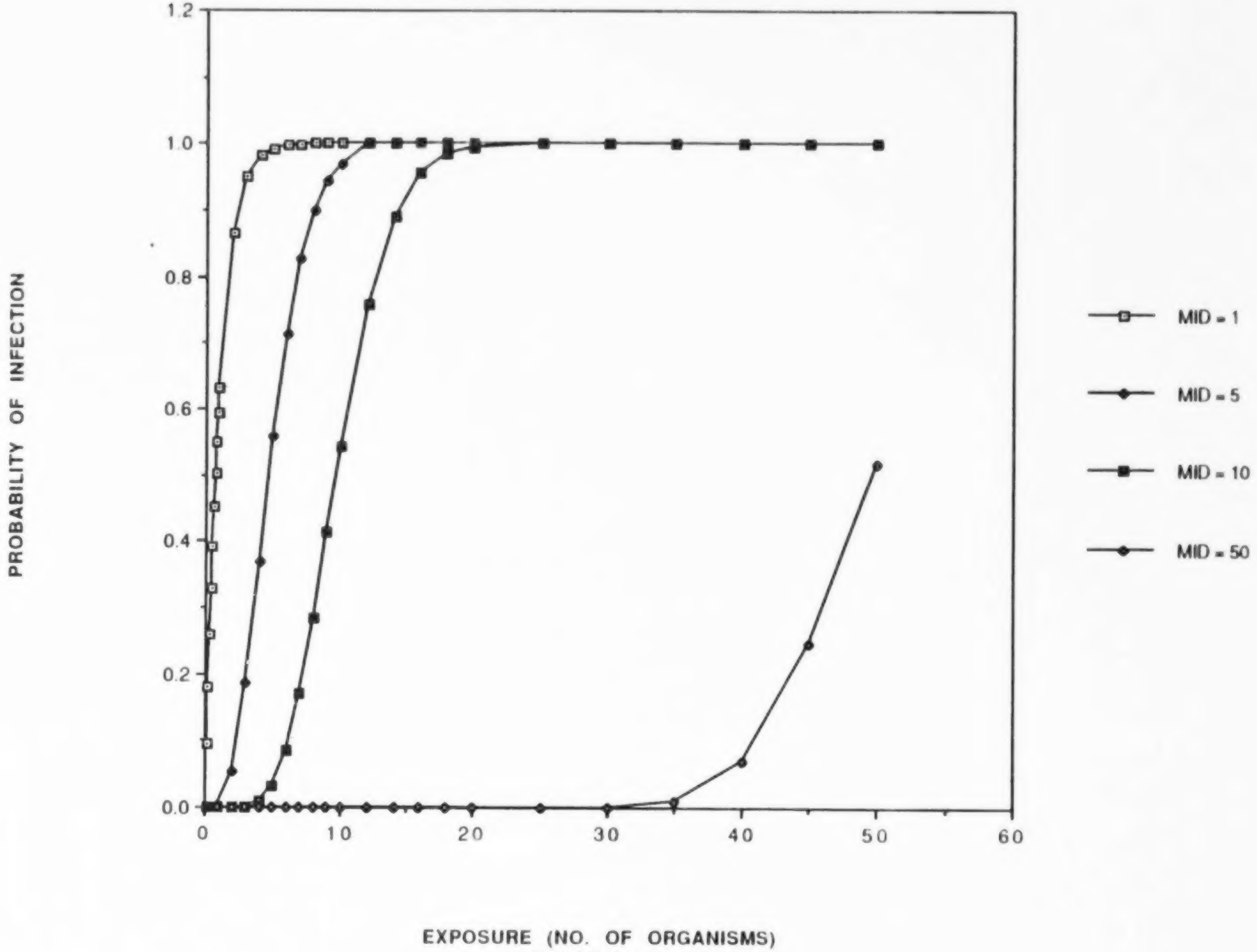

FIGURE 5-1

The particle size multiplier (k) varies with particle size range as follows:

Size range	<30 μm	<15 μm	<10 μm	<5 μm	<2.5 μm
k value	0.33	0.25	0.21	0.15	0.10

If the silt content of the soil is 40% and the size of particulates inhaled and ingested is in the <30 μm range, the calculated amount of particulates generated per hectare by tilling would be $6.04 \cdot 0.33 \cdot 0.4^{0.6} = 1.15$ kg/ha. The value of 40% silt corresponds to a loam or clay loam soil, and the size class chosen yields the highest estimated k factor, making this a conservative assumption.

For the model calculation, the operator of the tilling equipment is assumed to remain continuously in the particulate cloud generated by tilling. Therefore, the operator's exposure is equivalent to an 8-hour exposure to a particulate cloud whose concentration is given by the emission factor divided by the cloud volume per hectare. If, as a worst case, the operator is exposed at a height of 2 m and the cloud does not extend upward beyond 2 m, then the concentration of particulates in the cloud is 1150 g / $(2 \text{ m} \cdot 10^4 \text{ m}^2) = 0.058 \text{ g/m}^3$. The average respiration rate for adult males is 20 m^3/day. Allowing for a marginal increase in rate because of exertion, the operator might inhale 1 m^3/hour, or 8 m^3/working day. This value corresponds to 0.46 g particulates/day.

Tilling of the soil to incorporate liquid sludge occurs after the soil has dried appreciably. The model, therefore, arbitrarily assumes that the microbes will have mixed with the upper layer of soil, so that they are distributed in the upper 5% (0.75 cm) of the soil surface layer. Assuming a soil density of 1.33 g/cc, the associated soil layer would represent $1 \cdot 10^8$ g, and the concentration of pathogens in the particulate cloud would be given by (ASCRS • APRATE)/$1 \cdot 10^8$ g/ha. For liquid sludge, the suggested values of ASCRS [P(1)] = $5 \cdot 10^4$ pathogens/kg and APRATE [P(2)] = $1 \cdot 10^4$ kg/ha yield a concentration of 5 pathogens/g soil and an exposure of ~2.3 pathogens/working day. At an MID of 10, this exposure would yield a probability of infection of $1.4 \cdot 10^{-4}$.

The worst case exposure in Practices IV and V would occur if the particulate cloud were composed entirely of suspended particles of dried or composted sludge. The concentration of dust generated by tilling composted sludge is assumed to be 15 mg/m^3 (Clark et al., 1983). At a concentration of $1 \cdot 10^3$ bacterial pathogens/g, the exposure would be $8 \text{ m}^3\text{/day} \cdot 0.015 \text{ g/m}^3 \cdot 1 \cdot 10^3$ pathogens/g = 120 pathogens/day. This exposure would lead to a probability of infection of 1. To achieve a probability of infection <0.001/day, the bacterial pathogen exposure must be <3/day. Therefore, the calculation implies that, for tilling dry sludge, the prudent operator should wear a mask capable of filtering out 98% of the respirable particles.

The exposure calculation assumes that the dry sludge has the same particle size distribution as soil, which is probably not valid. Because of residual moisture, sludge is less likely to form a particulate cloud when it is tilled. In addition, tilling would result in a dilution of sludge with soil in the particulate cloud, and this dilution would reduce the exposure correspondingly. Clearly, more information is needed on the size and composition of airborne particulates generated by tilling newly-applied sludge.

5.2. PARTICULATES FROM SOIL SURFACE

The PARTICULATES (5) compartment represents a cloud of airborne particles generated from SOIL SURFACE (4), at a concentration determined by models for wind erosion. The time of initiation, strength and duration of the wind generating the particulate cloud can be specified by the user; default values are 18 m/sec (40 mph) for 6 hours, beginning at 60 hours.

The concentration of wind-generated dust in the air will depend on the soil composition, moisture, and wind speed. Exposure to windblown dust occurs only under dry conditions. There is a threshold wind speed below which wind erosion does not occur. That speed varies with soil type, terrain and amount of cover vegetation, and, because of large variations in wind speed close to the ground, is typically corrected to a height of 7 m. In this example, the corrected threshold wind speed is assumed to be 7.5 m/sec. The following estimates are based on the document Rapid Assessment of Exposure to Particulate Emissions from Surface Contamination Sites (U.S. EPA, 1985b), which summarizes methodologies to estimate concentrations of airborne pollutants. Assuming unlimited erosion potential (no ground cover), the emission factor for particles $<10\ \mu m$ in diameter (E_{10}) is given by the following equation (Gillette, 1981):

$$E_{10} = 0.036\ (1-V)\ ([u]/u_t)^3\ F(x) \tag{5-2}$$

where:

E_{10} = PM_{10} emission factor (average annual emission rate per unit area, in $g/m^2/hour$)

V = fraction of contaminated surface with cover vegetation (0 for bare soil)

$[u]$ = mean wind speed (m/sec)

u_t = threshold value of wind speed in m/sec, corrected for height of 7 m

x = $0.886\ u_t/[u]$

$F(x)$ = an empirical function tending to 1.91 as x becomes less than 0.5, and toward 0 as x becomes greater than 3. In practice, the calculation will be of little interest if [u] is not greater than u_t, so x will always be less than 0.886, and F(x) will be sufficiently close to 1.91 that use of that value will cause only a slight overestimate of E_{10}.

For a wind speed of 40 mph (18 m/sec) and no vegetation, E_{10} is calculated by this equation to be 0.95 $g/m^2/hour$, or 2.64 g/ha/sec.

5.2.1. Onsite Exposures. For onsite exposure, the concentration may be estimated by the following equation (Gifford and Hanna, 1973),

$$P = Cq_a/[u] \qquad (5\text{-}3)$$

or by the similar equation (Pasquill, 1974),

$$P = q_a x/[u]h' \qquad (5\text{-}4)$$

where:

q_a = area emission rate

$[u]$ = mean wind speed over emission area

C = constant dependent on characteristics of the pollutant and source

x = distance from upwind edge of source to receptor

h' = height of the box containing the cloud.

If $C = x/\sigma_z$ (Gifford & Hanna 1973),

$C = 1/0.012 = 83.3$, and

$P = 2.64 g/10^4\ m^2/sec * 83.3/18\ m/sec$

$= 12.2*10^{-4}\ g/m^3\ (1.2\ mg/m^3)$,

or from Pasquill (1974),

$P = (2.64\ g/10^4\ m^2/sec) * 400\ m/(18\ m/sec * 5m)$

$= 11.7*10^{-4}\ g/m^3$ (1.2 mg/m3).

These equations show satisfactory agreement at the distance chosen, which represents the human receptor at the downwind edge of a 10-ha field (250m * 400m). The former calculation, which implies an equilibrium condition at long distances but which may give an overestimate for short distances, is used in the model.

The highest concentration expected in SOIL SURFACE (4) is 12.5 pathogens/g, which would occur if composted sludge were incorporated at a rate of 25 T/ha and a concentration of $1*10^6$ pathogens/kg. Exposure to a particulate suspension of this soil at 1 mg/m^3 would lead to no significant probability of infection, even at MID=1.

5.2.2. Offsite Exposures. For offsite emissions, a Gaussian-plume model is used. Particulates are assumed to be evenly distributed throughout the defined volume of an aerosol cloud, and the pathogens associated with airborne material are assumed to be uniformly distributed among the particles. In this model the wind erosion equation can be applied, or the user may specify a weight of sludge-contaminated soil/ha that is transferred to an airborne state. The model then calculates the number of pathogens transferred with that weight of material by using the adjusted concentration of pathogens in surface soil (for Practice I default conditions, $5*10^4$ pathogens/kg sludge * $1*10^4$ kg sludge/ha / $2*10^9$ g soil/ha = 0.25 pathogens/g soil). This portion of the total pathogen population is transferred from SOIL SURFACE (4) to PARTICULATES (5). While it is more likely that viruses or bacteria will be found in wind-borne particulates than the heavier ova and cysts of parasites, each model pathogen is treated in the same manner.

The particulate-exposure risk calculation assumes that particulate-associated pathogens are disseminated downwind after generation and that generation is an instantaneous event. The downwind movement leads to a reduction in the concentration of airborne pathogens as a result of dispersion and inactivation. The reduction in pathogen concentration due to dispersion is estimated using a modification of Pasquill's diffusion equation, which describes release from a ground-level source with no plume rise (U.S. EPA, 1985b).

$$C_{x,y,z} = \frac{Q_T}{\pi \sigma_y \sigma_z u} e^{-(y^2/2\sigma_y^2)} e^{-(z^2/2\sigma_z^2)} \qquad (5\text{-}5)$$

where:

$C_{x,y,z}$ = number of pathogens per cubic meter of air at a downwind location described by the coordinates x,y,z after release from a source at ground level

Q_T = rate of release of pathogens from the source

$\sigma_{y,z}$ = standard deviation of the pathogen concentration in a lateral (y) and vertical (z) direction

u = mean wind speed (m/sec).

In the risk calculations, as a worst case, the exposed individual is assumed to be standing directly downwind (default $y=0$). The default value for height of exposure is 1.6 m. The user may specify the distance x in meters between the source and the exposed individual. The dispersion parameters ($\sigma_{y,z}$) in the model were determined for neutral atmospheric conditions.

The reduction in pathogens due to inactivation is affected by a number of factors including the age of the cloud, temperature, relative humidity, and solar radiation (Camann et al., 1978; Dimmick and Akers, 1969; Gregory, 1973; Lighthart and Frisch, 1976). The following equation was used to estimate inactivation of pathogens dispersed as shown in Equation 5-5.

$$I = e^{d(x/u)} \tag{5-6}$$

where:

I = inactivation of the pathogen population

e = base of natural logarithm

d = aerosol inactivation rate constant for a particular pathogen.

The inactivation rate constants used in the model are 50th percentile values for the aerosol inactivation rates of Salmonella and enteroviruses in water suspensions (Camann et al., 1978) and an estimated value for Ascaris. For particulate clouds association of microbes with the particles is assumed to be protective, and a decay rate equal to that in air-dried soil is used. The symbols $\underline{x}$ and $\underline{u}$ are as described for Equation 5-5.

The combined effects of dispersion and inactivation are in Equation 5-7, which predicts the final pathogen concentration.

$$C_{x,y,z} = \frac{Q_T}{\pi \sigma_y \sigma_z u} \; e^{-(y^2/2\sigma_y^2)} \; e^{-(z^2/2\sigma_z^2)} \; e^{d(x/u)} \tag{5-7}$$

where:

$C_{x,y,z}$ = number of pathogens/m^3 of air at a downwind location described by the coordinates x,y,z after release from a source at ground level

Q_T = calculated rate of release of pathogens from the source compartment at a given time ((mass/sec) * (pathogens/mass))

x = user-specified distance in meters from the source

y = lateral distance of the receptor in meters from a line directly downwind of the source

z = receptor height in meters

σ_y = 0.0295x, the standard deviation of particulate concentration perpendicular to the wind direction for a specified distance x in meters (Turner, 1969)

σ_z = 0.012x, the standard deviation of particulate concentration vertically (Turner, 1969)

d = inactivation rate constant. Values for soil particles are the same as for bulk soil. Values for water suspensions (Camann et al., 1978):

Salmonella -0.028/sec
Ascaris -0.01/sec
enterovirus -0.002/sec

u = user-specified wind speed (m/sec). The default value for WINDSP [P(25)]= 18 m/sec for windstorm and BREEZE [P(32)] = 4 m/sec for irrigation.

Using the calculated windstorm-generated source strength of 2.64 g/ha/sec and 0.25 pathogens/g soil, a source of 10 ha would give a concentration of $4.8 * 10^{-3}$ pathogens/m^3 at a distance of 200 m downwind. For aerosol and sludge intake the average inhalation rate is assumed to be 20 m^3/day or 0.83 m^3/hour. The pathogen exposures from offsite particulates are assumed not to exceed 16 hours/day, but for ease of computation, the inhalation rate is converted to 0.62 m^3/hour, and exposures in the compartment are accumulated hourly into a 24-hour pathogen exposure. A rough estimation of risk of infection can be made from these results. The distribution of pathogens on particles of different size classes is not well described. The equation used above models emissions based on a calculated source strength of particle <10 μm in diameter. This size class may represent approximately 20% of the total particulates, whereas pathogens are likely to be associated with larger particles as well. Therefore, the emissions might be higher by a factor of perhaps 4, or about $2 * 10^{-2}$ pathogens/m^3 at 200 m from the 10-ha source. A person breathing the dust-laden air for 16 hours/day at a rate of 20 m^3/day would inhale 13.3 m^3 of air, or 0.27 pathogens/day. The probability of infection is approximately $1.85 * 10^{-4}$ at this dose for organisms with MID as low as 4, and vanishingly small for higher MID values. The likelihood that any individual would remain exposed for 16 hours to a windstorm of this magnitude is small, so this estimate demonstrates an exaggerated worst case. In addition, any reductions in pathogen concentration by inactivation before the windstorm would reduce the exposure, and the presence of vegetation on the source field would reduce the concentration of suspended soil.

5.2.3. Tilling Operations. Additional tilling, at a time and for a duration specified by the user, is modeled by the same calculation as for the transfer from INCORPORATION (2) to APPLICATION/INCORPORATION EMISSIONS (3*), except, in this case, the calculation is performed for the transfer from SOIL SURFACE (4) to APPLICATION/INCORPORATION EMISSIONS (3*). The calculation is done once for each hour of the duration specified by the user. After complete mixing of the sludge into surface soil, at an application rate of $1*10^4$ kg liquid sludge/ha and a concentration of $5*10^4$ bacterial pathogens/kg, the average bacterial pathogen exposure for 8 hours of tilling would be approximately 0.46 g/day $*$ 0.25 pathogen/g = 0.115 pathogens/day. This exposure would result in a calculated probability of infection of $1*10^{-16}$ for MID=10 or 0.12 for MID = 1.

The distribution of dust in the particulate cloud would not, in all probability, be uniform. The tractor operator would be more likely to receive a lower dose than indicated by this calculation, whereas a person working at ground level in the field during the tilling operation would receive a higher dose. However, the ground-level worker would be unlikely to be exposed to the particulate cloud at full concentration for the entire work day, further reducing the probability of infection. Figure 5-1 shows that to achieve a probability of infection of 10^{-3}/day (with MID=10), the average exposure would have to be increased to approximately 3 bacterial pathogens/day, a factor of more than 25. Any dilution of the particulates by soil would reduce the pathogen concentration correspondingly, increasing the exposure required for infection.

5.3. DIRECT CONTACT

In Practice I, sludge is assumed to be tilled into the surface soil immediately after application. If the soil has a bulk density of 1.33 g/cm^3, the dry mass of the surface soil layer is $2*10^6$ kg/ha (Naylor and Loehr, 1982; Donahue et al., 1983). As a result of this mixing, the initial concentration of pathogens in the surface soil is given by the following equation:

$$CP = CS * AR/MS \qquad (5\text{-}8)$$

where:

CP = concentration of pathogens in soil (number/g)

CS = concentration of pathogens in sludge (number/kg)

AR = application rate (kg/ha)

MS = mass of soil = $2 \cdot 10^6$ kg/ha $\cdot$ 10^3 g/kg = $2 \cdot 10^9$ g/ha.

By this equation, application of liquid sludge with $5 \cdot 10^4$ pathogens/kg at a rate of $1 \cdot 10^4$ kg/ha would result in a soil concentration of 0.1 pathogen/g soil.

The default amount of ingested soil and residue is 0.1 g/day. Assuming an initial concentration of 0.1 pathogen/g soil, the daily exposure is 0.01 pathogen. For MID=10, the probability of infection would be much less than 10^{-16}.

5.4. WATER

5.4.1. **Surface Runoff.** Surface runoff occurs when the amount of water received by the field exceeds the retention capacity of the soil. The amount of runoff is calculated by a subroutine that is called once for each rainfall or irrigation event. This subroutine uses the Modified Universal Soil Loss Equation (Williams, 1975), which calculates the amount of soil erosion as a function of soil condition and use and as a function of the peak discharge, calculated from a constructed excess rainfall hyetograph. Inputs to the subroutine include the time, duration, and amount of rainfall. Rainfall is modeled as a single event whose intensity increases linearly with time to a peak at a user-specified storm-advancement coefficient (default value 0.4) and subsequently falls linearly to the end of the rain. The composite transport resulting from excess rainfall serves as the transfer function from SOIL SURFACE (4) to SURFACE RUNOFF (6). Irrigation is assumed to be controlled so that it does not cause surface runoff.

The majority of soil microorganisms are associated with soil particles. A fraction of these will be suspended by soil surface water and will be transported in suspension by surface runoff. Studies have shown that the fraction of microorganisms suspended by excess water is dependent on properties of the soil as well as on type of microorganism (Burge and Enkiri, 1978; Drewey and Eliassen, 1968; Gerba el al., 1975; Marshall, 1971; Reddy et al., 1981). Data on adsorption of viruses and bacteria to soil particles can be fitted empirically to an equation describing a linear chemical adsorption isotherm:

$$PARTIC = K * SUSP$$

where:

PARTIC = concentration of soil-bound organisms, number/gram

K = retention coefficient

SUSP = concentration of suspended organisms, number/ml solution.

Reported values of K range from 260 to 1900 for bacteria (Matson et al., 1978) and from 4.6 to 161 for viral particles (Burge and Enkiri, 1978).

Because the total number of organisms in SURFACE RUNOFF (6*) is the sum of bound and suspended organisms (TOTAL = PARTIC + SUSP), the number of suspended organisms is

$$SUSP = TOTAL/(1 + K) \text{ or}$$

$$SUSP/TOTAL = 1/(1 + K).$$

The constant $1/(1 + K)$ is variable SUSPND [P(45)]. Default values for SUSPND vary with pathogen type and also with land use practice; it is assumed that suspension of organisms in soil surface water is less when there is a grass cover (Practices II, III, and V) than when there is a substantial fraction of bare ground (Practices I and IV). Default values of SUSPND [P(45)] are given in Table A-2.

The human receptor for surface runoff is a swimmer who incidentally ingests 0.1 L of pond water during a single swim. Although some of the microbes transported into SURFACE RUNOFF (6*) will be associated with sediment and are likely to be deposited at the bottom of the pond, swimming by the human receptor is likely to resuspend them and they can be ingested. The model assumes that all pathogens transported to the runoff pond remain uniformly distributed.

Assuming a pond volume of 100 m^3 per hectare, an infective concentration (3 Salmonella per 100 mL) represents $3 \cdot 10^6$ organisms per hectare, or about 0.6% of the initial pathogen load when liquid sludge is applied at 10 T/ha. Test runs of the surface runoff subroutine show that a 2-hour rainfall beginning at 120 hours would have to total nearly 4.65 cm to yield a total of even 0.15% of the pathogen load as surface transport. Of that amount, slightly over 50% would be suspended organisms. This amount of rainfall is well above the 5-year maximum 2-hour rainfall reported for any agricultural region of the continental United States, so a release of that amount would be an infrequent occurrence.

5.4.2. Groundwater at an Offsite Well. The groundwater subroutine considers transport in saturated soil. Computer models for solute transport in groundwater have been applied to the transport of microbes in soil (Haridas, 1983; van Genuchten, 1978, 1986). These models must include terms for the death or inactivation of microbes, filtration, retardation, adsorption and advection during transport. Clogging of soil pores by filtration and the subsequent declogging by sloughing off of biofilm can be modeled (Haridas, 1983), but time-averaged values for retardation are adequate and are more readily estimated. The mathematical description used in this model is a one-dimensional solution (van Genuchten and Alves, 1982) of the advection-dispersion equation for solutes (for a description, see Volume II: User's Manual). Input parameters include retardation coefficients for saturated soil, as well as distance from source to output (upper boundary of groundwater or location in field to drinking water well), bulk flow velocity and hydrodynamic dispersion. Default values for these variables are given in Table A-6. The value of the retardation coefficient R is chosen to represent poor adsorption to soil particles during saturated flow.

Accurate values for retardation coefficient R are not known; values may be very high for extreme adsorption, filtering or clogging or as low as 0.5 for selective flow of pathogens through large pores and channels (Keswick et al., 1982; Bradford, 1987; Matthess et al., 1988). For the saturated flow option, a default value of 1 (no retardation) is used.

Both surface soil and subsurface soil immobilize microorganisms to some extent. As input into the groundwater transport subroutine, the surface soil is represented as retaining all but 0.05% of bacteria and 0.1% of virus particles. The default fraction for transport of bacterial and viral pathogens through the unsaturated zone is 0.001. Transport through the saturated zone is modeled for a default distance of 50 m from the edge of the field, with the source of saturated flow taken as a point source containing all of the contribution from 1 ha.

A probability of infection of 10^{-3} requires an accumulated daily exposure of 3 pathogens when MID=10. At the modeled water consumption rate of 2 L/day, this would require a concentration of 1.5 pathogens/L. Using the default values for thickness of the aquifer (AQUIFR [P(9)]) and porosity (POROS [P(10)], the volume of groundwater per hectare is $3*10^4$ m^3 or $3*10^7$ L. The total number of pathogens applied in liquid sludge is assumed to be $5*10^8$ per hectare, so the potential maximum groundwater contamination, if all pathogens were transported immediately, would be $5*10^8/3*10^7 = 17$ pathogens/L. A maximum of 0.1% of soil surface pathogens is estimated to be transported to subsurface soil, and 0.1% of subsurface soil pathogens are likely to be transported to groundwater (Sorber and Moore, 1987). Therefore, the maximum likely exposure to sludge pathogens in drinking water should not exceed ~0.2/day.

5.4.3. Fugitive Emissions (Aerosols) from Irrigation. Direct onsite exposure to contaminated irrigation water is assumed to be negligible. However, aerosols are generated by spray irrigation. Sample calculations show that use of GROUNDWATER (9) as a source of irrigation water is not likely to lead to significant pathogen concentrations in the aerosol. As a worst case, the use of treated liquid sludge for irrigation is modeled in Practices II and III. The default rate of irrigation is 0.5 cm/hour, or 50 m^3/ha/hour. At 5% sludge solids, this rate is equivalent to $2.5 \cdot 10^3$ kg/ha/hour, or 695 g/ha/sec. The efficiency of aerosol formation during spraying has been estimated as about 0.1% or less (Sorber et al., 1984), giving a value of 0.695 g/ha/sec or about $7 \cdot 10^{-5}$ g/m^2/sec for the rate of total emissions. If the concentration of pathogens in liquid sludge is $5 \cdot 10^4$ pathogens/kg, the area emission rate Q_a is

$$Q_a = (7 \cdot 10^{-5}\ \text{g/m}^2\text{/sec}) \cdot 50\ \text{pathogens/g}$$

$$= 3.5 \cdot 10^{-3}\ \text{pathogens/m}^2\text{/sec}$$

and the concentration of airborne pathogens P is

$$P = 83.3\ Q_a/[u]$$

$$= (83.3 \cdot 3.5 \cdot 10^{-3}\ \text{pathogens/m}^2\text{/sec})/\ (4\ \text{m/sec})$$

$$= 7.3 \cdot 10^{-2}\ \text{pathogens/m}^3.$$

This concentration would lead to a 5-hour exposure of ~0.4 pathogens for a moderately active worker in the field (probability of infection approximately $8 \cdot 10^{-12}$).

Fugitive emissions from irrigation spray nozzles are modeled by use of equation 5-7 above. The human receptor for this exposure is assumed to be a person working outdoors 200 m downwind from the closest irrigation sprayer. Inputs to the subroutine include the time at which irrigation begins, the duration and amount of irrigation, wind speed and the concentration of pathogens in the irrigation water. Inactivation rates are taken to be the 50th percentile values for the aerosol inactivation rates of Salmonella and enteroviruses (Camann et al., 1978) and an estimated value for Ascaris. They are as follows:

d = Salmonella -0.028/sec
Ascaris -0.01/sec
enterovirus -0.002/sec

Offsite fugitive emissions from a 10-ha source under irrigation would be calculated according to equation 5-7 above, using values of 4 m/sec for u and the inactivation constants given above. According to this calculation, the concentration of bacterial pathogens at 200 m offsite would be

$$C_{200} = 0.39 \text{ pathogens/m}^3.$$

A 5-hour exposure to this concentration would lead to inhalation/ingestion of about 2 bacterial pathogens for a probability of infection of $3.8 * 10^{-5}$ for MID = 10.

The above discussions for particulates indicate that the probability of adverse consequences from exposure to aerosols would be minimal. In addition, studies on the consequences of spraying treated and untreated wastewater have indicated that no health risks could be associated with the use of treated wastewater (Camann et al., 1980; Fannin et al., 1980; Johnson et al., 1980; Northrop et al., 1980; Shuval and Fattal, 1980). Field studies on the application of wastewater at Kibbutz Tzora, Israel (Teltsch and Katzenelson, 1978) showed that when raw wastewater containing 0-60 Salmonella per 100 mL was sprayed, the average airborne concentration of Salmonella at 40 m was $0.014/m^3$. At an inhalation rate of 1 m^3/hour, a 12-hour exposure to this concentration of organisms would yield an inhaled dose of about 0.17 organisms.

5.5. CROPS/PRODUCTS

If contaminated water is used for irrigation, the crop can potentially be contaminated. If an aboveground crop (tomato) of 10 cm diameter retains all of the pathogens in a 0.2-mm layer on the surface of the fruit, the equivalent volume of irrigation water is approximately 0.01 L. A probability of 10^{-3} for infection with the pathogen at MID=10 would require a concentration of 300 pathogens/L. Using the calculation given above (Section 5.4.1) that the surface runoff pond concentration could be 30 pathogens/L after a 2-hour rainfall of 4.65 cm or (in Section 5.4.2) that the potential maximum groundwater contamination would be 17 pathogens/L, the probability of contamination of crop units to an infectious level by irrigation water would be negligible.

6. SOURCES OF UNCERTAINTY

Many factors contribute to the uncertainties associated with the present risk assessment model, chief among these being the lack of quantitative data. Even when available, data are highly variable with regard to (1) the initial concentrations of microbial pathogens in infectious waste, wastewater and sludge; (2) processes of microbial transport and inactivation; and (3) dose-response relationships. Estimates of levels of uncertainty of some other contributing factors are given in Table 6-1.

The most obvious factor contributing to uncertainty of the model is imprecise exposure data. Most of the source materials involve a number of poorly characterized taxa of organisms distributed heterogeneously through a nonhomogeneous medium. Variations in pathogen numbers in the applied sludges due to seasonal and yearly differences can influence exposure levels. The initial concentrations of pathogens in treated sludge are usually not known precisely, and estimates of changes in these concentrations within and between compartments of each sludge management practice are rarely supported. Such estimates are subsequently used to calculate the pathogen concentration at different points of human exposure. Consequently, the resulting estimated concentrations may be incorrect by orders of magnitude. As an example, concentrations of pathogens in groundwater depend on (1) the number of organisms that enter the soil; (2) their transport into the groundwater, a factor dependent upon soil type and the particular pathogen, and the distance through soil to groundwater; and (3) survivability of the pathogen in the particular soil and groundwater environment. Since these factors are only approximately known at best, predicting exposure levels due to groundwater contamination is extremely difficult.

Similarly, uncertainties in the prediction of pathogen transport by aerosols center around estimates of percent aerosolization, biological decay and variations in wind direction and strength. The greatest uncertainty in this exposure assessment resides in the estimates of biological decay. Responses of pathogens to treatment conditions and interactions of pathogen types with environmental conditions differ. Further, responses of receptor human populations to pathogens introduced by different exposure routes are complex.

Another factor that produces error in human exposure determination is the volume of contaminated sample consumed. If exposure is through contaminated food, the quantity of sludge or soil on the food and the quantity of food consumed are subject to large variations. If exposure occurs through consumption of water while swimming,

TABLE 6-1

Levels of Uncertainty Associated with Pathogen Risk Assessment

Category		Contribution to Uncertainty
1.	Determination of immune status	One order of magnitude
2.	Assay technique	One order of magnitude
3.	Sensitivity of host	Several orders of magnitude
4.	Virulence of virus	Several orders of magnitude
5.	Use of upper 95% confidence limit	Up to one order of magnitude
6.	Route of exposure	One order of magnitude
7.	Choice of dose-response model	Several orders of magnitude
8.	Synergism/antagonism	Many orders of magnitude
9.	Dietary considerations	Uncertain
10.	Distribution of subjects among doses and number used	1-2 orders of magnitude

Source: Gerba, 1984

variations in the volume of water consumed by different individuals is likely. Even the quantity of drinking water consumed by different persons can vary greatly.

The dose required to cause infection is another major source of potential error. Based on information generated with human respiratory and enteric viruses, a virus capable of infecting a specific tissue culture can also infect humans. Thus, a single infectious unit (I.U.) of virus, as detected in tissue culture, is considered a minimum infective dose for purposes of this report. If the tissue culture assay is insensitive, the actual infectious dose could be considerably less than 1 I.U. On the other hand, the value may be much greater than 1 I.U., as has been determined for echovirus-12 in infected volunteers (Schiff et al., 1984). Similar sources of error are associated with assessing risk in the case of other enteric pathogens. In general, the uncertainties in measuring infectious dose greatly weaken the power of this type of quantitative risk assessment.

Any consideration of factors that introduce uncertainties to the model must include the very concept of using representative organisms. Though widely accepted, the assumption that the species selected accurately represents the potential pathogens present in the source material is not necessarily reliable. Other sources of error, such as the immune state and resulting susceptibility of the individual to infection by a particular pathogen, and the route of entry of the pathogens, will alter the probability of infection.

7. SENSITIVITY ANALYSIS

7.1. INTRODUCTION

The goals and objectives for model application determine the nature of the model. Two categories of models can be distinguished: research models and management models. The research model should provide indicators for future directions in investigations. The possibility for gaining an understanding of response of the system to input parameters is of primary importance. Management models have specified applications, e.g., long-term planning, evaluation of a specific design, etc. The RISK model is a research-oriented model at this stage, and the main objectives of model testing and sensitivity analysis are to better comprehend the system, especially its response to varying the input parameters, and to narrow the future research directions.

7.2. MODEL TESTING

The main attributes of software quality include reliability, usability, efficiency, transportability and maintainability. The listed quality factors are related to testing, sensitivity analysis, validation and verification issues. Program testing (i.e., running the code with representative sample data sets and comparing the actual results with the expected results) has been the fundamental technique for determining coding errors. Because testing is a difficult and time-consuming procedure, increased emphasis should be placed on ensuring quality throughout the entire process of code development, rather than trying to add it after the process is complete. Although all errors in the software are costly, the later in the life cycle that errors are discovered, the more costly the error. The objective of the verification process is twofold: to check the accuracy of the computational algorithms used to solve the governing equation, and to assure that the computer code is fully operational. Verification is also used to evaluate the sensitivity of the code to various parameter values. Sample problems should be selected so that the main program and all subroutines are tested. Model validation is often defined as the comparison of model results with actual measurements from the field or laboratory experiments. The objective is to determine how well the model describes the actual system behavior. Validation of environmental models is quite difficult to perform because of the lack of field data and questionable accuracy of the data. Collected field data are often published in some earlier studies for a different purpose, often without any quality assurance and quality control, and thus they are subject to inaccuracies, interpretive bias, loss of information during transmission, and so forth. The modeling procedure, before and after any field experiment has been used to test the validity of the model, can be considered to reflect a priori and a posteriori knowledge of the behavior of a system (Beck, 1983).

Sensitivity analysis can yield insight into the nature of the model. A priori sensitivity analysis establishes the relative magnitudes of changes in the simulated model output responses to changes in the model parameter values. A posteriori sensitivity analysis examines the distribution of model responses that are possible, given the distributions of estimated parameter values.

7.3. SENSITIVITY ANALYSIS

Even without experimental field data having been collected for model evaluation, certain important questions about the suitability of the model can be posed. The answers to these questions -- questions of a priori sensitivity analysis -- may lead to a restructuring of the model at the conceptualization stage (Beck, 1983). Sensitivity analysis is part of a feedback loop during both the a priori and a posteriori phases of the modeling procedure.

The importance of sensitivity analysis has been well known in control engineering since the 1950s (Tomovic, 1962). Relatively recently has it been applied to water quality and ecological systems, for example by Gardner et al. (1981), Haas (1983), Jaffe and Parker (1978), McCuen (1973), and Rose and Swartzman (1981). In groundwater literature, the question of sensitivity analysis has been discussed by Gilham and Farvolden (1974) and by Sykes et al. (1983, 1985).

The main objective of the sensitivity analysis is to understand the relative sensitivity of the model predictions (output) to changes in the values of the model input parameters β. The sensitivity coefficient S_{ij} can be defined as

$$S_{ij} = \frac{\Delta C_i/\bar{C}_i}{\Delta\beta_j/\bar{\beta}_j}$$

where:

ΔC_i = the change in the i-th state variable of the model in response to a change $\Delta\beta_j$ in the value of the j-th input parameter;

$\bar{C}_i$ = the nominal value for the i-th predicted state variable response (e.g., a number of pathogens in a given compartment);

$\bar{\beta}_j$ = the nominal value for the j-th input parameter.

In general, ΔC_i and $\Delta \beta_j$ are introduced as small changes in the neighborhoods of $\overline{C}_i$ and $\overline{\beta}_j$. The formula given above enables the researcher to investigate whether a certain percentage change in a parameter has no real significance ($S_{ij}=0$), whether a parameter is a dominant parameter, or whether a small change in the value of the input parameter causes instability in the model output.

If the output response of the model is found to be insensitive to changes in the value of any parameter, that parameter is characterized as not identifiable. This means that it is not possible to estimate the influence of that parameter unless the model relationships are specified in some other form. On the other hand, if a parameter has a strong influence on a particular output variable, then the quality of that output will depend strongly on the ability to make accurate estimates of the value of the input parameter.

7.4. METHODOLOGY

Before sensitivity analysis begins, one must know the nominal values for the input parameters. A "complete" analysis requires the estimation of frequency distributions for the set of parameters that will be varied. As a minimum, enough information must be available to estimate the limits of variability. The nominal, minimum, and maximum values of the input model parameters are given in Table 7-1. The sensitivity analysis was performed for Practice I only (Application of Liquid Sludge for Production of Commercial Crops for Human Consumption) and for the pathogen Salmonella.

Once the nominal values for the parameters were selected, an input data set in which the values were varied separately was created. The "reference run" is for a period of 60 days, and includes 5 rain events that occur at 120, 240, 480, 600, and 840 hours of the total simulation time. All 16 compartments of the model had no pathogens at the beginning of the simulation. The results were printed every 24 hours. The value of parameter ASCRS (P[1]) was 1E10 for all runs. The relatively large value of the parameter was chosen only for purpose of the sensitivity analysis and should not be considered representative of actual sludge applications.

Only one input parameter was changed at a time, for each run, taking the maximum or the minimum value of the parameter. After each run, the output file PATHOUT was examined. The file contains information on number of pathogens in each of 16 compartments and the infection probability for the specified PRINT SAMPLING RATE (every 24 hours in this case). It was decided that of the 16 compartments, only compartments that represent sources of human exposure be monitored. The monitored

TABLE 7-1
INPUT VARIABLES - PRACTICE I. SALMONELLA

#	NAME	Nominal	Minimum	Maximum	Comments
1	ASCRS*	1.0E+10	1.0E+10	1.0E+10	Unsupported Value
2	APRATE	1.00E+4	2.00E+3	7.00E+4	
3	ASCIN	-	-	-	calculated
4	TREG	**	**	**	crop specific
5	UPLIM	1.00E+9	1.00E+9	1.00E+9	upper limit for pathogen population
6	APMETH	+1	0	-1	
7	AREA	10	1	100	
8	TEMP	20	0	43	
9	AQUIFR	10	2	50	
10	POROS	0.3	.1	.5	
11	FILTR8	2	1	4	
12	MID	10	1	10,000	
13	TRAIN	168	-2		see subroutine RAINS
14	RDEPTH	5	2.5	10	
15	TK				time since rain
16	TIRRG	0	0	0	time since irrigation
17	IRMETH	0	0	1	
18	DILIRR	0	0	1	
19	NIRRIG	2	1	4	
20	IRRATE	0.5	0.1	1	irrigation rate
21	DEPTH	2.5	0.5	10	
22	COUNT				
23	TWIND	60	30	120	
24	DWIND	6	3	12	
25	WINDSP	18	4	22.4	
26	EPSMLT	0.33	0.1	0.33	
27	ESILT	0.4	0.2	0.8	
28	EHT	2	0.5	3	
29	SCRIT	7.5	3.75	15.0	
30	COVER	0	0	0.1	
31	AEREFF	0.001	0.0001	0.01	
32	BREEZE	4	1	22.4	
33	HT	1.6	1	2	
34	ANDAY	-	-	-	calculated
35	TMAX	-	-	-	user specified
36	TMIN	-	-	-	user specified
37	SLOPES*	0.0206	0.0412	0.0103	
38	NTRCPS*	2.113	2.113	2.113	
39	SLOPEP*	0.00449	0.0089	0.00225	
40	NTRCPP*	1.435	1.435	1.435	
41	ASLSUR	0.9	1.0	-	unsupported estimate
42	FSSUR	1	1	1	
43	FRRAIN				see subroutine RAINS
44	SUBSOL*	5.00E-4	5.00E-6	5.00E-2	
45	SUSPND*	5.00E-3	5.00E-5	5.00E-1	

TABLE 7-1 (Continued)
INPUT VARIABLES - PRACTICE I. SALMONELLA

#	NAME	Nominal	Minimum	Maximum	Comments
46	FCROP1	1.00E-8	1.00E-10	1.00E-6	unsupported estimate
47	FCROP2	0.06	0.0006	6	Practice I and IV only; unsupported
48	FCROP3	1.00E-3	1.00E-5	1.00E-1	Practice I and IV only; unsupported
49	FCROP4	1.00E-4	1.00E-6	1.00E-2	unsupported estimate
50	FCROP5	0.012	0.00012	1.2	unsupported estimate
51	FCROP6	0	0	0	
52	FCROP7	2.00E-4	2.00E-6	2.00E-2	unsupported estimate
53	FRGRND*	0.001	0.0001	0.01	
54	SSWTCS*	-	-	-	Practice II,III, and V only
55	PSTMG	-	-	-	Practice V only
56	CSTSS	-	-	-	Practice II, III, and V only
57	SSTCS	-	-	-	Practice II and III only
58	CSTSSW	0.75	0.1	1.0	unsupported estimate
59	DTCTMT	-	-	-	Practice II and III only
60	DTCTMK	-	-	-	
61	TMTSS	-	-	-	Practice II only
62	TMTH	-	-	-	Practice II and III only
63	TMTU	-	-	-	
64	HTM	-	-	-	Practice II and III only
65	UTM	-	-	-	
66	CROP	1	0	-1	
67	TCULT	-2	-2	0	
68	TCROP	720	360	1440	
69	THARV	1848	924	3696	
70	YIELD1	2.50E+7	2.50E+6	2.50E+8	
71	YIELD2	2.50E+7	2.50E+6	2.50E+8	
72	YIELD3	1.00E+6	1.00E+5	1.00E+7	
73	HAY	-	-	-	Practice II and III only
74	PLNT1	-	-	-	Practice IV only
75	PLNT2	-	-	-	Practice IV only
76	PLNT3	-	-	-	Practice IV only
77	PPG	-	-	-	PPG = N(16)/YIELD for Practice I
78	CATTLE	-	-	-	Practice II and III only
79	COWS	-	-	-	Practice II and III only
80	STORAG	-	-	-	Practice III only
81	FORAG	-	-	-	Practice II and III only
82	ALFALF	-	-	-	Practice III only
83	SCNSMP	-	-	-	Practice II and III only
84	FATTEN	-	-	-	Practice III only
85	TSLOTR	-	-	-	Practice II and III only

* pathogen specific, Table A-2 User's Manual

** practice and crop-specific

compartments are 3, 5, 6, 7, 12, 13, and 16. The infection probability was monitored for each of the five exposure categories: Onsite Person, Offsite Person, Food Consumer, Groundwater Drinker and Pond Swimmer. The number of pathogens in a compartment or the infection probability versus time was extracted from the PATHOUT file. Thus, in addition to four "normal" output files, twelve data files were generated for each run. Even for the limited number of input parameters being tested, a large number of output files have been generated (~1000 files). Each of the output data files was sorted to find the maximum. Those values were entered in a spreadsheet, and the sensitivity coefficients were calculated for each compartment (Tables 7-2 through 7-5). In addition, graphs were generated for visual examination of the results (a selected number of these, Figures 7-1 through 7-7, are included).

7.5. RESULTS AND COMMENTS

The results of the sensitivity analysis are given in Tables 7-2 through 7-5. The tables do not include Compartments 3 (Application/Tilling Emissions), 5 (Particulates), and 16 (Commercial Crop) because they did not contain any pathogens for any combination of the input parameters.

The number of pathogens in Compartment 6 (Surface Runoff) (Table 7-2) was most sensitive to SLOPES (P[37]), a process function parameter for inactivation of organisms in soil; AREA (P[7]), area of the field; APRATE (P[2]), application rate; APMETH (P[6]), application method; NIRRIG (P[19]), number of irrigations per week; and SUSPND (P[45]), a parameter for fraction of organisms transferred from soil surface to soil surface water.

The number of pathogens in Compartment 7 (Direct Contact) (Table 7-3) was sensitive to SLOPES (P[37]), a process function parameter for inactivation of organisms in soil; AREA (P[7]), area of the field; APMETH (P[6]), application method; and APRATE (P[2]), application rate.

The number of pathogens in Compartment 12 (Offsite Well) (Table 7-4) was most sensitive to SLOPES (P[37]), a process function parameter for inactivation of organisms in soil; IRRATE (P[20]), irrigation rate; APRATE (P[2]), application rate; AREA (P[7]), area of the field; SUBSOL (P[44]), a parameter for fraction of organisms transferred from soil surface to subsurface soil; and FRGRND (P[53]), a parameter for fraction of organisms transferred from subsurface soil to groundwater. AQUIFR (P[9]), aquifer thickness and POROS (P[10]), porosity of the aquifer, did not have any effect on the number of pathogens in the compartment; these parameters are applied in the risk

TABLE 7-2
SENSITIVITY ANALYSIS PRACTICE I*
NUMBER OF PATHOGENS IN COMPARTMENT 6

P	INPUT			OUTPUT			SENSITIVITY	
	NOM	MIN	MAX	NOM	MIN	MAX	Si(MIN)	Si(MAX)
2	1.00E+04	2.00E+03	7.00E+04	7.055E+08	1.411E+08	4.939E+09	1.0000	1.0001
6	1.00E+00	0.00E+00	-1.00E+00	7.055E+08	0.000E+00	7.055E+08	1.0000	0.0000
7	1.00E+01	1.00E+00	1.00E+02	7.055E+08	0.000E+00	7.059E+08	1.1111	0.0001
8	2.00E+01	0.00E+00	4.30E+01	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
9	1.00E+01	2.00E+00	5.00E+01	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
10	3.00E-01	1.00E-01	5.00E-01	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
11	2.00E+00	1.00E+00	4.00E+00	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
12	1.00E+01	1.00E+00	1.00E+04	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
14	5.00E+00	2.50E+00	1.00E+01	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
19	2.00E+00	1.00E+00	4.00E+00	7.055E+08	7.092E+08	7.015E+08	0.0105	0.0057
20	5.00E-01	1.00E-01	1.00E+00	7.055E+08	7.059E+08	7.055E+08	0.0007	0.0000
21	2.50E+00	5.00E-01	1.00E+01	7.055E+08	7.052E+08	7.055E+08	0.0005	0.0000
23	6.00E+01	3.00E+01	1.20E+02	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
24	6.00E+00	3.00E+00	1.20E+01	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
25	1.80E+01	4.00E+00	2.24E+01	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000

* Results derived from this sensitivity analysis should not be considered representative of actual sludge applications.

TABLE 7-2 (Continued)
SENSITIVITY ANALYSIS PRACTICE I*
NUMBER OF PATHOGENS IN COMPARTMENT 6

P	INPUT			OUTPUT			SENSITIVITY	
	NOM	MIN	MAX	NOM	MIN	MAX	Si(MIN)	Si(MAX)
27	4.00E-01	2.00E-01	8.00E-01	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
28	2.00E+00	5.00E-01	3.00E+00	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
29	7.50E+00	3.75E+00	1.50E+01	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
31	1.00E-03	1.00E-04	1.00E-02	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
32	4.00E+00	1.00E+00	2.24E+01	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
37	2.06E-02	4.12E-02	1.03E-02	7.055E+08	5.856E+06	3.012E+09	0.9917	6.5386
39	4.49E-03	8.90E-03	2.25E-03	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
44	5.00E-04	5.00E-06	5.00E-02	7.055E+08	7.059E+08	6.690E+08	0.0006	0.0005
45	5.00E-03	5.00E-05	5.00E-01	7.055E+08	7.112E+08	2.431E+08	0.0082	0.0066
46	1.00E-08	1.00E-10	1.00E-06	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
53	1.00E-03	1.00E-04	1.00E-02	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
58	7.50E-01	1.00E-01	1.00E+00	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
68	7.20E+02	3.60E+02	1.44E+03	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
69	1.85E+03	9.24E+02	3.70E+03	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000
70	2.50E+07	2.50E+06	2.50E+08	7.055E+08	7.055E+08	7.055E+08	0.0000	0.0000

* Results derived from this sensitivity analysis should not be considered representative of actual sludge applications.

TABLE 7-3
SENSITIVITY ANALYSIS PRACTICE I*
NUMBER OF PATHOGENS IN COMPARTMENT 7

P	INPUT			OUTPUT			SENSITIVITY	
	NOM	MIN	MAX	NOM	MIN	MAX	Si(Min)	Si(MAX)
2	1.00E+04	2.00E+03	7.00E+04	1.232E+02	2.464E+01	8.625E+02	1.0000	1.0001
6	1.00E+00	0.00E+00	-1.00E+00	1.232E+02	0.000E+00	1.232E+02	1.0000	0.0000
7	1.00E+01	1.00E+00	1.00E+02	1.232E+02	0.000E+00	1.233E+02	1.1111	0.0001
8	2.00E+01	0.00E+00	4.30E+01	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
9	1.00E+01	2.00E+00	5.00E+01	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
10	3.00E-01	1.00E-01	5.00E-01	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
11	2.00E+00	1.00E+00	4.00E+00	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
12	1.00E+01	1.00E+00	1.00E+04	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
14	5.00E+00	2.50E+00	1.00E+01	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
19	2.00E+00	1.00E+00	4.00E+00	1.232E+02	1.232E+02	1.226E+02	0.0000	0.0049
20	5.00E-01	1.00E-01	1.00E+00	1.232E+02	1.233E+02	1.233E+02	0.0010	0.0008
21	2.50E+00	5.00E-01	1.00E+01	1.232E+02	1.232E+02	1.233E+02	0.0000	0.0003
23	6.00E+01	3.00E+01	1.20E+02	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
24	6.00E+00	3.00E+00	1.20E+01	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
25	1.80E+01	4.00E+00	2.24E+01	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000

* Results derived from this sensitivity analysis should not be considered representative of actual sludge applications.

TABLE 7-3 (Continued)
SENSITIVITY ANALYSIS PRACTICE I*
NUMBER OF PATHOGENS IN COMPARTMENT 7

P	INPUT			OUTPUT			SENSITIVITY	
	NOM	MIN	MAX	NOM	MIN	MAX	Si(MIN)	Si(MAX)
27	4.00E-01	2.00E-01	8.00E-01	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
28	2.00E+00	5.00E-01	3.00E+00	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
29	7.50E+00	3.75E+00	1.50E+01	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
31	1.00E-03	1.00E-04	1.00E-02	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
32	4.00E+00	1.00E+00	2.24E+01	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
37	2.06E-02	4.12E-02	1.03E-02	1.232E+02	2.265E+01	2.072E+02	0.8162	1.3636
39	4.49E-03	8.90E-03	2.25E-03	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
44	5.00E-04	5.00E-06	5.00E-02	1.232E+02	1.233E+02	1.168E+02	0.0008	0.0005
45	5.00E-03	5.00E-05	5.00E-01	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
46	1.00E-08	1.00E-10	1.00E-06	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
53	1.00E-03	1.00E-04	1.00E-02	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
58	7.50E-01	1.00E-01	1.00E+00	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
68	7.20E+02	3.60E+02	1.44E+03	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
69	1.85E+03	9.24E+02	3.70E+03	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000
70	2.50E+07	2.50E+06	2.50E+08	1.232E+02	1.232E+02	1.232E+02	0.0000	0.0000

* Results derived from this sensitivity analysis should not be considered representative of actual sludge applications.

TABLE 7-4
SENSITIVITY ANALYSIS PRACTICE I*
NUMBER OF PATHOGENS IN COMPARTMENT 12

P	INPUT			OUTPUT			SENSITIVITY	
	NOM	MIN	MAX	NOM	MIN	MAX	Si(Min)	Si(MAX)
2	1.00E+04	2.00E+03	5.00E+07	4.846E+04	9.691E+03	3.392E+05	1.0000	0.0012
6	1.00E+00	0.00E+00	-1.00E+00	4.846E+04	1.129E+08	4.846E+04	2328.76	0.0000
7	1.00E+01	1.00E+00	1.00E+02	4.846E+04	0.000E+00	3.459E+02	1.1111	0.1103
8	0.00E+00	0.00E+00	4.30E+01	4.846E+04	4.846E+04	4.846E+04	ERR	ERR
9	1.00E+01	2.00E+00	5.00E+01	4.913E+04	4.913E+04	4.913E+04	0.0000	0.0000
10	3.00E-01	1.00E-01	5.00E-01	4.913E+04	4.913E+04	4.913E+04	0.0000	0.0000
11	2.00E+00	1.00E+00	4.00E+00	4.846E+04	4.817E+04	4.862E+04	0.0120	0.0033
12	1.00E+01	1.00E+00	1.00E+04	4.846E+04	4.846E+04	4.846E+04	0.0000	0.0000
14	5.00E+00	2.50E+00	1.00E+01	4.846E+04	4.846E+04	4.846E+04	0.0000	0.0000
19	2.00E+00	0.00E+00	4.00E+00	4.846E+04	4.853E+04	9.018E+04	0.0014	0.8609
20	5.00E-01	1.00E-01	1.00E+00	4.846E+04	0.000E+00	4.482E+03	1.2500	0.9075
21	2.50E+00	5.00E-01	1.00E+01	4.846E+04	7.751E+04	2.171E+04	0.7493	0.1840
23	6.00E+01	3.00E+01	1.20E+02	4.846E+04	4.846E+04	4.846E+04	0.0000	0.0000
24	6.00E+00	3.00E+00	1.20E+01	4.846E+04	4.846E+04	4.846E+04	0.0000	0.0000
25	1.80E+01	4.00E+00	2.24E+01	4.846E+04	4.846E+04	4.846E+04	0.0000	0.0000

* Results derived from this sensitivity analysis should not be considered representative of actual sludge applications.

TABLE 7-4 (Continued)
SENSITIVITY ANALYSIS PRACTICE I*
NUMBER OF PATHOGENS IN COMPARTMENT 12

P	INPUT			OUTPUT			SENSITIVITY	
	NOM	MIN	MAX	NOM	MIN	MAX	Si(Min)	Si(MAX)
27	4.00E-01	2.00E-01	8.00E-01	4.846E+04	4.846E+04	4.846E+04	0.0000	0.0000
28	2.00E+00	5.00E-01	3.00E+00	4.846E+04	4.846E+04	4.846E+04	0.0000	0.0000
29	7.50E+00	3.75E+00	1.50E+01	4.846E+04	4.846E+04	4.846E+04	0.0000	0.0000
31	1.00E-03	1.00E-04	1.00E-02	4.846E+04	4.846E+04	4.846E+04	0.0000	0.0000
32	4.00E+00	1.00E+00	2.24E+01	4.846E+04	4.846E+04	4.846E+04	0.0000	0.0000
37	2.06E-02	4.12E-02	1.03E-02	4.846E+04	1.228E+04	7.484E+04	0.7466	1.0887
39	4.49E-03	8.90E-03	2.25E-03	4.846E+04	4.846E+04	4.846E+04	0.0000	0.0000
44	5.00E-04	5.00E-06	5.00E-02	4.846E+04	4.846E+02	4.844E+06	1.0000	0.9996
45	5.00E-03	5.00E-05	5.00E-01	4.846E+04	4.846E+04	4.813E+04	0.0000	0.0001
46	1.00E-08	1.00E-10	1.00E-06	4.846E+04	4.846E+04	4.846E+04	0.0000	0.0000
53	1.00E-03	1.00E-04	1.00E-02	4.846E+04	4.846E+03	4.845E+05	1.0000	0.9998
58	7.50E-01	1.00E-01	1.00E+00	4.846E+04	4.846E+04	4.846E+04	0.0000	0.0000
68	7.20E+02	3.60E+02	1.44E+03	4.846E+04	4.846E+04	4.846E+04	0.0000	0.0000
69	1.85E+03	9.24E+02	3.70E+03	4.846E+04	4.846E+04	4.846E+04	0.0000	0.0000
70	2.50E+07	2.50E+06	2.50E+08	4.846E+04	4.846E+04	4.846E+04	0.0000	0.0000

* Results derived from this sensitivity analysis should not be considered representative of actual sludge applications.

TABLE 7-5
SENSITIVITY ANALYSIS PRACTICE*
NUMBER OF PATHOGENS IN COMPARTMENT 13

P	INPUT			OUTPUT			SENSITIVITY	
	NOM	MIN	MAX	NOM	MIN	MAX	Si(MIN)	Si(MAX)
2	1.00E+04	2.00E+03	7.00E+04	0.000E+00	0.000E+00	0.000E+00	ERR	ERR
6	1.00E+00	0.00E+00	-1.00E+00	0.000E+00	0.000E+00	0.000E+00	ERR	ERR
7	1.00E+01	1.00E+00	1.00E+02	0.000E+00	0.000E+00	0.000E+00	ERR	ERR
8	2.00E+01	0.00E+00	4.30E+01	0.000E+00	0.000E+00	0.000E+00	ERR	ERR
9	1.00E+01	2.00E+00	5.00E+01	0.000E+00	0.000E+00	0.000E+00	ERR	ERR
10	3.00E-01	1.00E-01	5.00E-01	0.000E+00	0.000E+00	0.000E+00	ERR	ERR
11	2.00E+00	1.00E+00	4.00E+00	0.000E+00	0.000E+00	0.000E+00	ERR	ERR
12	1.00E+01	1.00E+00	1.00E+04	0.000E+00	0.000E+00	0.000E+00	ERR	ERR
14	5.00E+00	2.50E+00	1.00E+01	0.000E+00	0.000E+00	0.000E+00	ERR	ERR
19	2.00E+00	1.00E+00	4.00E+00	0.000E+00	0.000E+00	1.732E+01	ERR	ERR
20	5.00E-01	1.00E-01	1.00E+00	0.000E+00	0.000E+00	0.000E+00	ERR	ERR
21	2.50E+00	5.00E-01	1.00E+01	0.000E+00	0.000E+00	6.033E+00	ERR	ERR
23	6.00E+01	3.00E+01	1.20E+02	0.000E+00	0.000E+00	0.000E+00	ERR	ERR
24	6.00E+00	3.00E+00	1.20E+01	0.000E+00	0.000E+00	0.000E+00	ERR	ERR
25	1.80E+01	4.00E+00	2.24E+01	0.000E+00	0.000E+00	0.000E+00	ERR	ERR

* Results derived from this sensitivity analysis should not be considered representative of actual sludge applications.

TABLE 7-5 (Continued)
SENSITIVITY ANALYSIS PRACTICE*
NUMBER OF PATHOGENS IN COMPARTMENT 13

P	INPUT			OUTPUT			SENSITIVITY	
	NOM	MIN	MAX	NOM	MIN	MAX	Si(MIN)	Si(MAX)
27	4.00E-01	2.00E-01	8.00E-01	0.00E+00	0.00E+00	0.00E+00	ERR	ERR
28	2.00E+00	5.00E-01	3.00E+00	0.00E+00	0.00E+00	0.00E+00	ERR	ERR
29	7.50E+00	3.75E+00	1.50E+01	0.00E+00	0.00E+00	0.00E+00	ERR	ERR
31	1.00E-03	1.00E-04	1.00E-02	0.00E+00	0.00E+00	0.00E+00	ERR	ERR
32	4.00E+00	1.00E+00	2.24E+01	0.00E+00	0.00E+00	0.00E+00	ERR	ERR
37	2.06E-02	4.12E-02	1.03E-02	0.00E+00	0.00E+00	0.00E+00	ERR	ERR
39	4.49E-03	8.90E-03	2.25E-03	0.00E+00	0.00E+00	0.00E+00	ERR	ERR
44	5.00E-04	5.00E-06	5.00E-02	0.00E+00	0.00E+00	0.00E+00	ERR	ERR
45	5.00E-03	5.00E-05	5.00E-01	0.00E+00	0.00E+00	0.00E+00	ERR	ERR
46	1.00E-08	1.00E-10	1.00E-06	0.00E+00	0.00E+00	0.00E+00	ERR	ERR
53	1.00E-03	1.00E-04	1.00E-02	0.00E+00	0.00E+00	0.00E+00	ERR	ERR
58	7.50E-01	1.00E-01	1.00E+00	0.00E+00	0.00E+00	0.00E+00	ERR	ERR
68	7.20E+02	3.60E+02	1.44E+03	0.00E+00	0.00E+00	0.00E+00	ERR	ERR
69	1.85E+03	9.24E+02	3.70E+03	0.00E+00	0.00E+00	0.00E+00	ERR	ERR
70	2.50E+07	2.50E+06	2.50E+08	0.00E+00	0.00E+00	0.00E+00	ERR	ERR

* Results derived from this sensitivity analysis should not be considered representative of actual sludge applications.

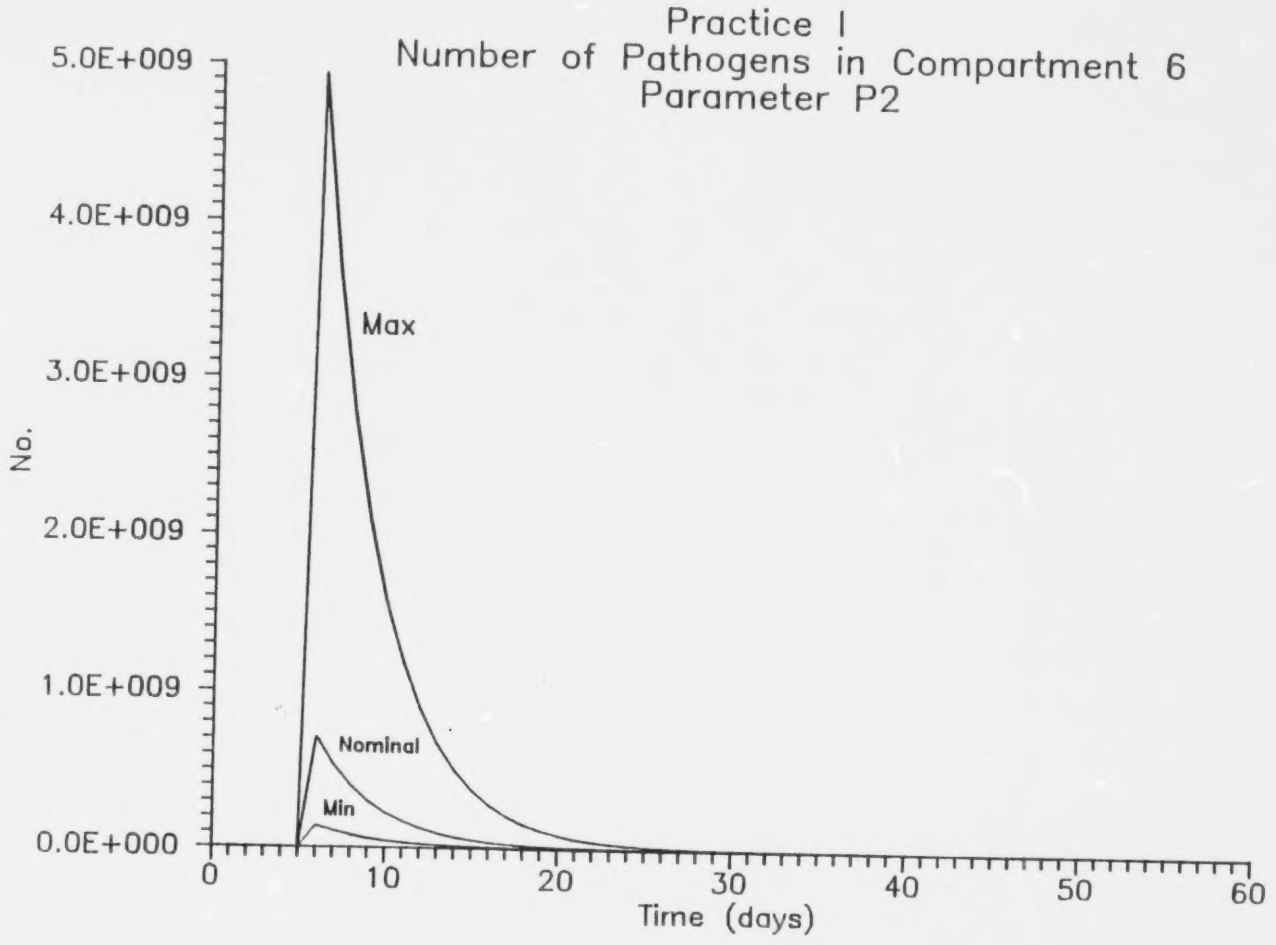
Practice I
Number of Pathogens in Compartment 6
Parameter P2
No.
5.0E+009
4.0E+009
3.0E+009
2.0E+009
1.0E+009
0.0E+000
0
10
20
30
40
50
60
Time (days)
Max
Nominal
Min

FIGURE 7-1

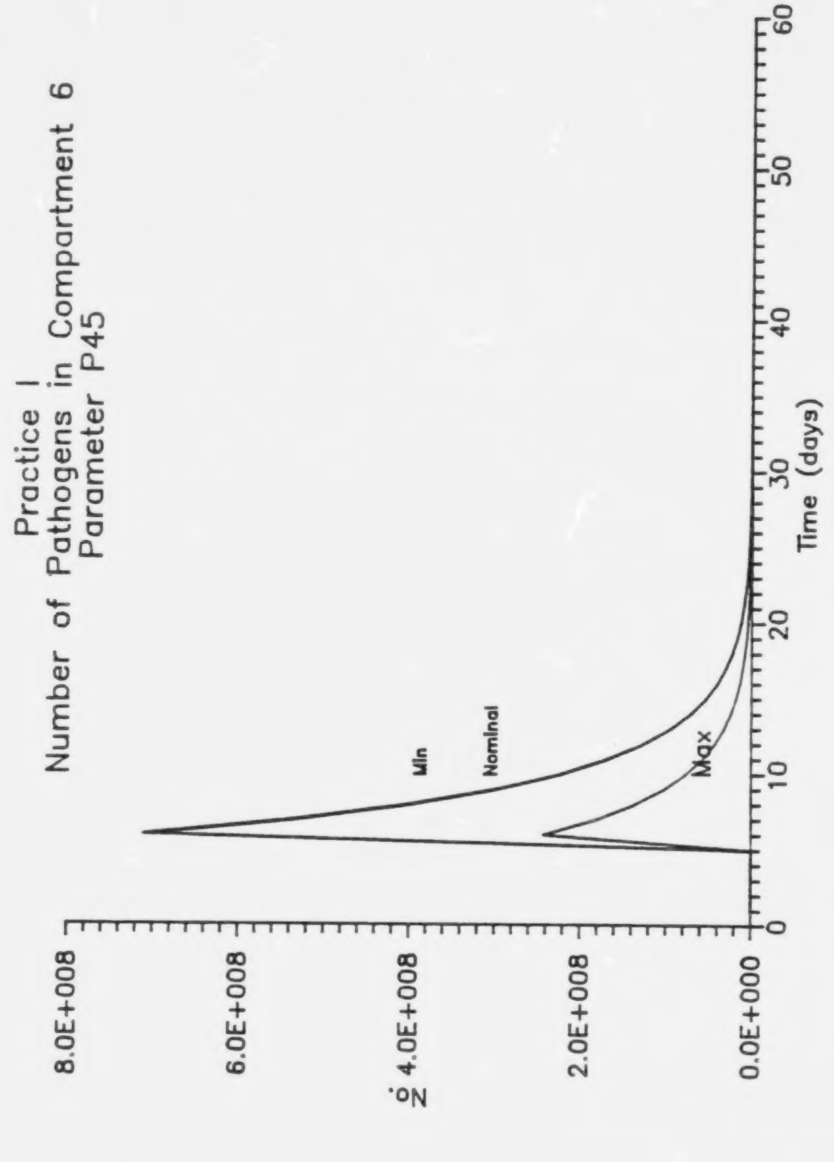
Practice I
Number of Pathogens in Compartment 6
Parameter P45
No.
8.0E+008
6.0E+008
4.0E+008
2.0E+008
0.0E+000
0
10
20
30
40
50
60
Time (days)
Min
Nominal
Max

FIGURE 7-2

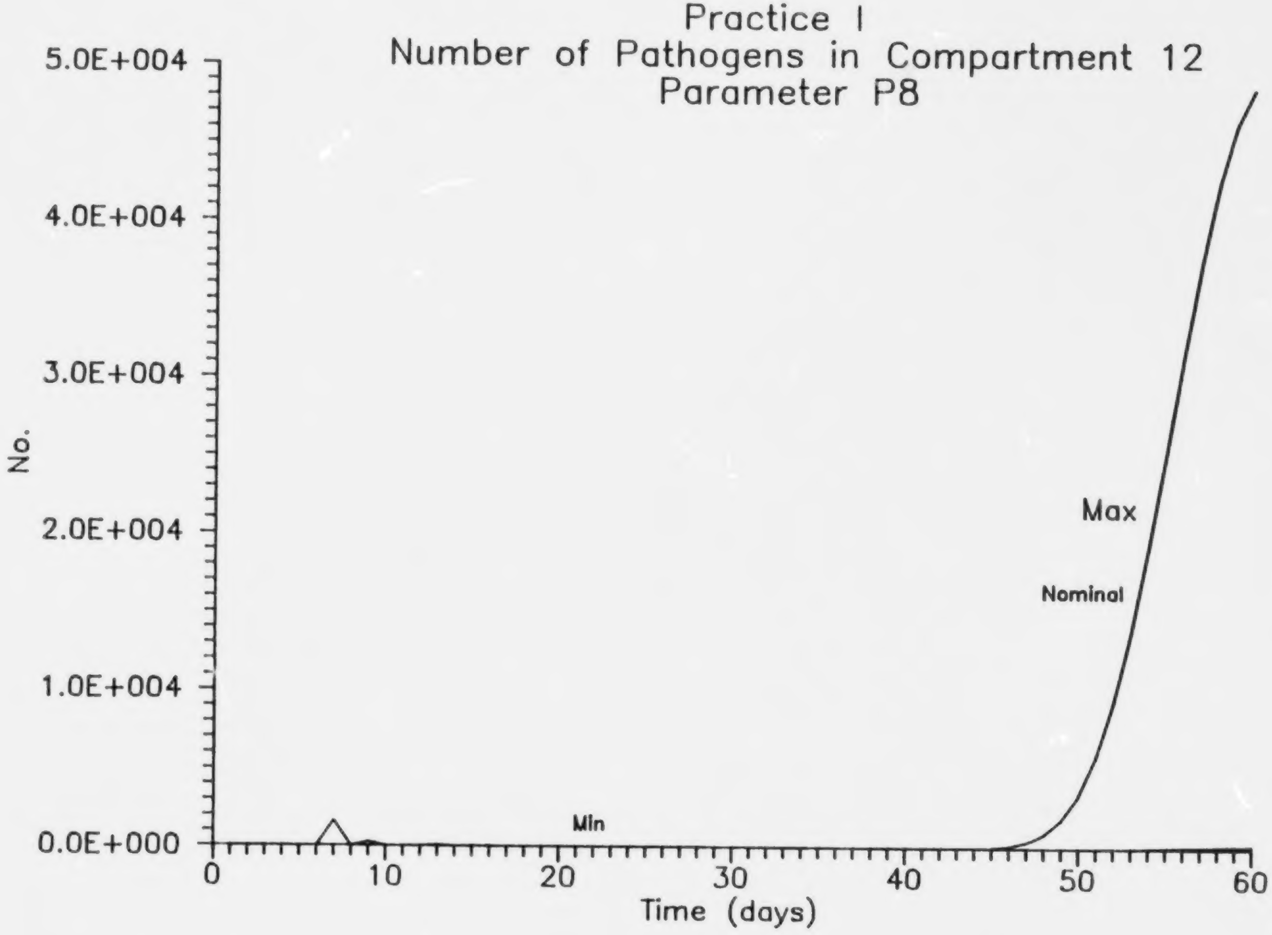
Practice I
Number of Pathogens in Compartment 12
Parameter P8
No.
5.0E+004
4.0E+004
3.0E+004
2.0E+004
1.0E+004
0.0E+000
0
10
20
30
40
50
60
Time (days)
Max
Nominal
Min

FIGURE 7-3

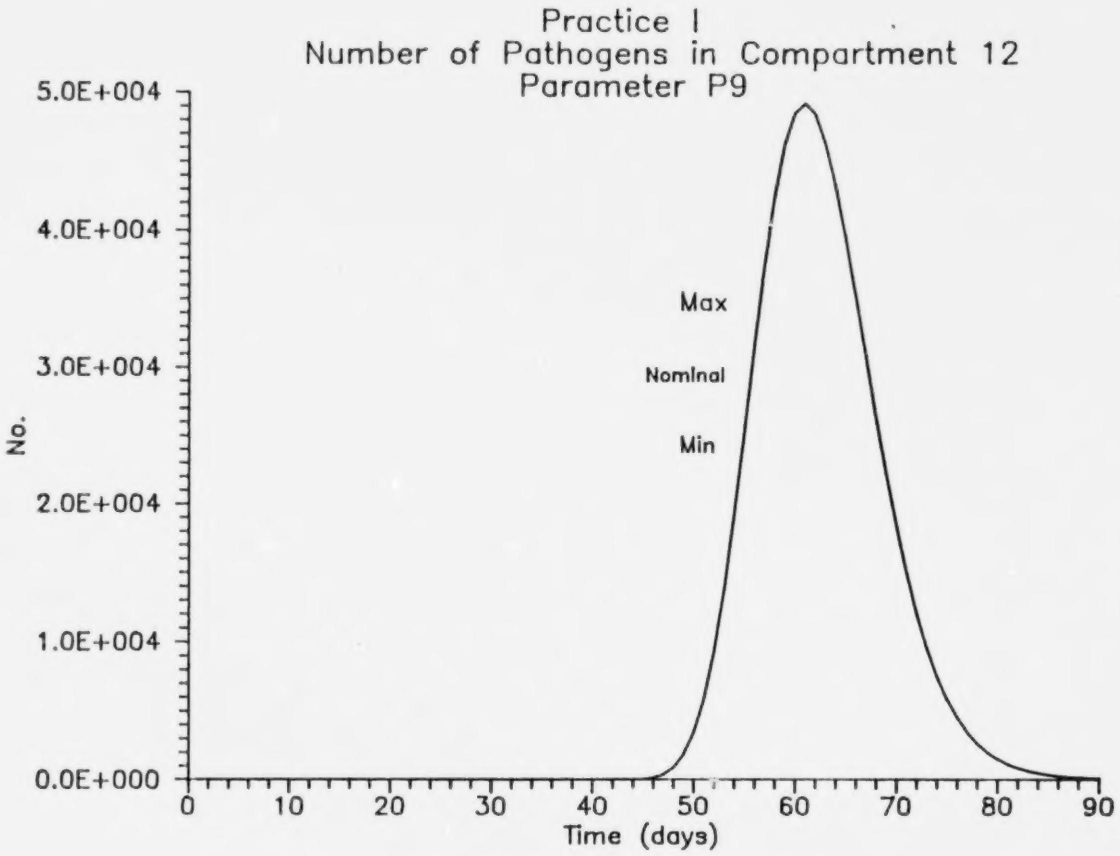
Practice I
Number of Pathogens in Compartment 12
Parameter P9
5.0E+004
4.0E+004
3.0E+004
2.0E+004
1.0E+004
0.0E+000
No.
Max
Nominal
Min
0
10
20
30
40
50
60
70
80
90
Time (days)

FIGURE 7-4

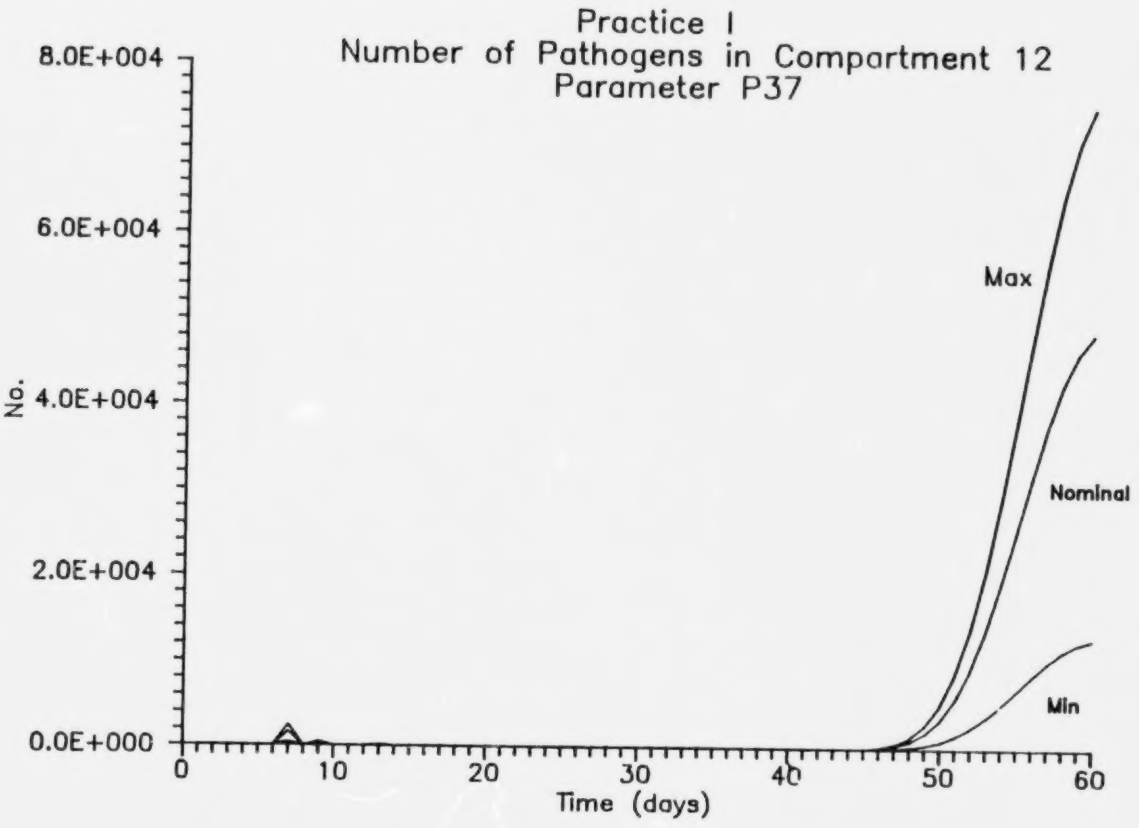
Practice I
Number of Pathogens in Compartment 12
Parameter P37
No.
8.0E+004
6.0E+004
4.0E+004
2.0E+004
0.0E+000
0
10
20
30
40
50
60
Time (days)
Max
Nominal
Min

FIGURE 7-5

PRACTICE I
ONSITE PERSON INFECTION PROBABILITY
PARAMETER P2

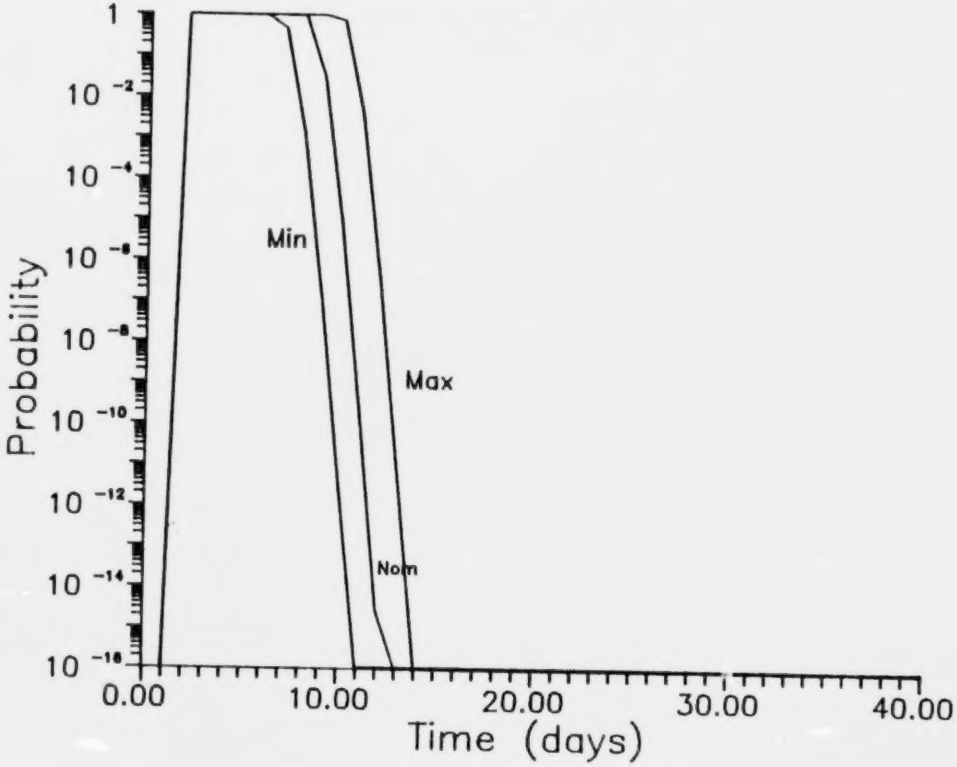

FIGURE 7-6

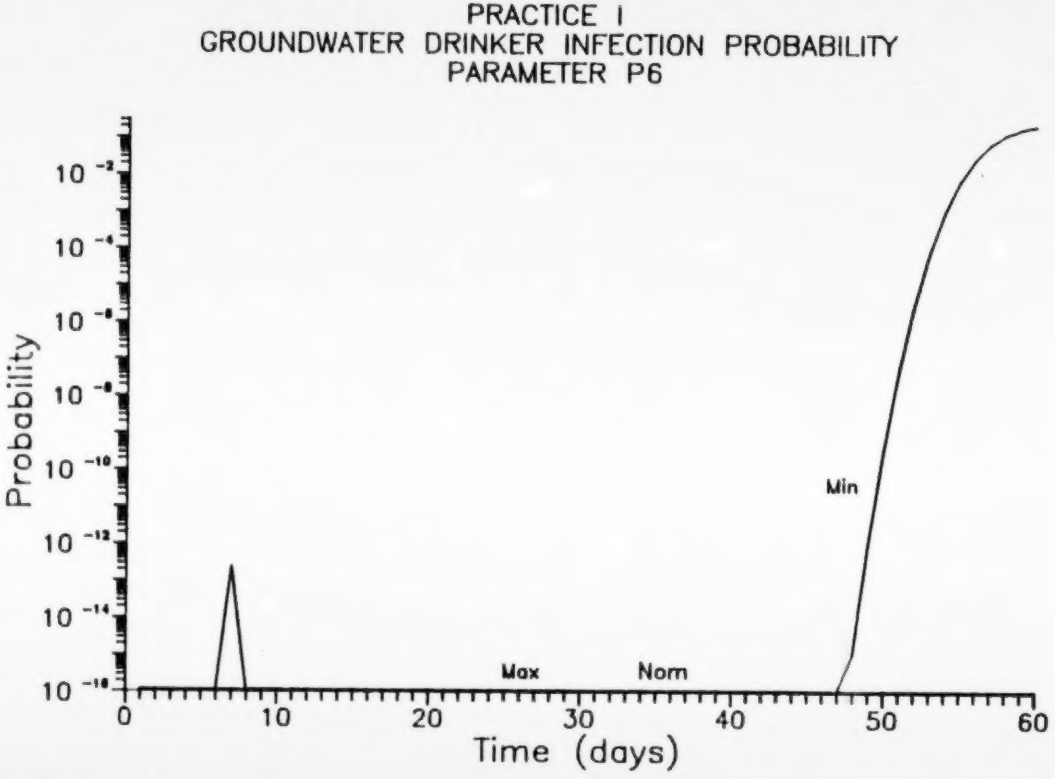
PRACTICE I
GROUNDWATER DRINKER INFECTION PROBABILITY
PARAMETER P6
Probability
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
Min
Max
Nom
0
10
20
30
40
50
60
Time (days)

FIGURE 7-7

calculation to calculate the concentration of pathogens.

Compartment 13 (Aerosols) (Table 7-5) was essentially empty for all runs except for the maximum values of NIRRIG (P[19]), number of irrigations per week, and DEPTH (P[21]), depth of irrigation water. Because the nominal value of the output variable was 0, the sensitivity coefficient could not be calculated for these parameters.

Most of the exposure compartments were shown to be sensitive to the same input variables. The sensitivity to SLOPES (P[37]) is more extreme when Compartment 12 (Offsite Well) is examined because SLOPES is an exponential parameter and the time between application of sludge and entry of pathogens into groundwater is relatively long. In contrast, the sensitivity coefficients of all output compartments for parameter P[2] (APRATE) reflect the proportional response of total number of pathogens applied to the amount of sludge applied. The sensitivity coefficients of Compartment 12 for SUBSOL (P[44]) and FRGRND (P[53]) reflect the role of these parameters in determining the number of pathogens entering groundwater from surface soil and subsurface soil. The response to variable P[6] (APMETH) is characteristic of the role of this parameter as a flag indicating the method of application of sludge; the value of P[6] labeled MIN in this analysis indicates subsurface application of sludge, which makes pathogens unavailable for surface runoff to Compartment 6 and makes more pathogens available for incorporation into groundwater and thus to Compartment 12.

Because of the large number of input parameters and the uncertainty related to the values of parameters, this sensitivity analysis should be viewed as preliminary. However, the analysis does indicate that the model is very sensitive to the inactivation rate of microorganisms in soil, as well as to the parameters used to calculate the fractions of pathogens transferred from surface soil to subsurface soil, from subsurface soil to groundwater and from surface soil to surface runoff water. Accordingly, these parameters should be selected with great care, especially as they are all likely to be site-specific. Because the data available to support choices of the values are limited, research efforts should be directed to these areas in order to increase the accuracy of the model.

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APPENDIX A. VARIABLES AND DEFAULT VALUES

TABLE A-1

Position Number, Name, Default Values, and Definition of Input Variables

Position	Name	Default Value I	Default Value II	Default Value III	Default Value IV	Default Value V	Definition
1	ASCRS	#	#	#	#	#	Pathogen density (Pathogens/kg)
2	APRATE	1×10^4	1.25×10^4	1.25×10^4	2.5×10^4	2.5×10^4	Application rate (kg/ha)
3	ASCIN	0	0	0	0	0	Pathogen concentration (Pathogens/ha)
4	TREG	**	**	**	**	**	Waiting period (months) required by U.S. EPA Pathogen Reduction Regulations
5	UPLIM	1×10^9	1×10^9	1×10^9	1×10^9	1×10^9	Upper limit for pathogen concentration
6	APMETH	+1	-1	-1	+1	+1	Application method
7	AREA	10	10	10	0.015	0.05	Area of field or garden (ha)
8	TEMP	--	--	--	--	--	Air temperature (^{0}C)
9	AQUIFR	10	10	10	10	10	Aquifer thickness (m)
10	POROS	0.3	0.3	0.3	0.3	0.3	Aquifer porosity
11	FILTR8	2	2	2	2	2	Infiltration rate (cm/hr)
12	MID	*	*	*	*	*	Minimum infective dose (number of pathogens)
13	TRAIN	-2	-2	-2	-2	-2	Time of rainfall (hr)
14	RDEPTH	5	5	5	5	5	Rainfall depth (cm)
15	TK	--	--	--	--	--	Time since last rain began
16	TIRRG	--	--	--	--	--	Time since last irrigation began
17	IRMETH	0	0	0	0	0	Irrigation method
18	DILIRR	0	1	1	0	0	Fraction of irrigation water that is contaminated
19	NIRRIG	2	2	2	2	2	Number of irrigations per week
20	IRRATE	0.5	0.5	0.5	0.5	0.5	Irrigation rate: (cm/hr)
21	DEPTH	2.5	2.5	2.5	2.5	2.5	Depth of irrigation water (cm)
22	COUNT	0	0	0			Pathogen concentration in irrigation sludge (pathogens/kg)
23	TWIND	60	60	60	60	60	Time of windstorm (hr)
24	DWIND	6	6	6	6	6	Duration of windstorm (hrs)
25	WINDSP	18	18	18	18	18	Wind speed during windstorm (m/sec)
26	EPSMLT	0.33	0.33	0.33	0.33	0.33	Particle size multiplier for tilling emissions
27	ESILT	0.4	0.4	0.4	0.4	0.4	Fractional silt content of soil
28	EHT	2	2	2	2	2	Height of box model (m)
29	SCRIT	7.5	7.5	7.5	7.5	7.5	Critical windspeed (m/sec)

TABLE A-1 (Continued)

Position Number, Name, Default Values, and Definition of Input Variables

Position	Name	Default Value					Definition
		I	II	III	IV	V	
30	COVER	0	0.9	0.9	0	0.9	Percent of ground surface covered by vegetation
31	AEREFF	0.001	0.001	0.001	0.001	0.001	Efficiency of aerosol formation
32	BREEZE	4	4	4	4	4	Normal wind speed (m/sec)
33	HT	1.6	1.6	1.6	1.6	1.6	Height of receptor downwind (m)
34	ANDAY	--	--	--	--	--	Day in annual temperature cycle, set by user
35	TMAX	#	#	#	#	#	Maximum monthly average temperature (calculated)
36	TMIN	#	#	#	#	#	Minimum monthly average temperature (calculated)
37	SLOPES•	•	•	•	•	•	Slope of inactivation vs temperature curve, moist soil
38	NTRCPS•	•	•	•	•	•	Intercept of inactivation vs temperature curve, moist soil
39	SLOPEP•	•	•	•	•	•	Slope of inactivation vs temperature curve, dry soil
40	NTRCPP•	•	•	•	•	•	Intercept of inactivation vs temperature curve, dry soil
41	ASLSUR	0.9	0.9	0.9	0.9	0.9	Transfer fraction: Application to soil surface
42	FSSUR	1	1	1			Transfer fraction: Application to subsurface soil
43	FRRAIN	--	--	--	--	--	Transfer fraction: Soil surface to surface runoff
44	SUBSOL•	•	•	•	•	•	Transfer fraction: Soil surface to subsurface soil
45	SUSPND•	•	•	•	•	•	Transfer fraction: Soil surface to soil surface water
46	FCROP1	1×10^{-8}			1×10^{-8}		Transfer fraction: Soil surface to crop 1
47	FCROP2	0.006			0.006		Transfer fraction: Soil surface to crop 0
48	FCROP3	1×10^{-3}			1×10^{-3}		Transfer fraction: Soil surface to crop -1
49	FCROP4	1×10^{-4}			1×10^{-4}		Transfer fraction: Crop 1 to soil surface
50	FCROP5	0.012			0.012		Transfer fraction: Crop 0 to soil surface
51	FCROP6	0			0		Transfer fraction: Crop -1 to soil surface
52	FCROP7	2×10^{-4}			2×10^{-4}		Transfer fraction: Subsurface soil to crop -1
53	FRGRND•	•	•	•			Transfer fraction: Subsurface soil to groundwater
54	SSWTCS•		•	•		•	Transfer fraction: Soil surface water to crop surface
55	PSTMG					0.5	Transfer fraction: Grass removed during mowing
56	CSTSS		0.01	0.01		0.01	Transfer fraction: Crop surface to soil surface
57	SSTCS		1×10^{-5}	1×10^{-5}			Transfer fraction: Soil surface to crop surface
58	CSTSSW	0.75	0.5	0.5	0.75	0.5	Transfer fraction: Crop surface to soil surface water
59	DTCTMT		0	0			Transfer fraction: Animal consumption to meat

TABLE A-1 (Continued)

Position Number, Name, Default Values, and Definition of Input Variables

Position	Name	Default Value I	II	III	IV	V	Definition
60	DTCTMK		0	0			Transfer fraction: Animal consumption to milk
61	TMTSS		0.7				Transfer fraction: Manure to soil surface
62	TMTH		0.001	0.001			Transfer fraction: Manure to hide
63	TMTU		0.001	0.001			Transfer fraction: Manure to udder
64	HTM		0.1	0.1			Transfer fraction: Hide to meat
65	UTM		0.05	0.05			Transfer fraction: Udder to milk
66	CROP	1					Type of crop
67	TCULT	-2			-2		Cultivation time (hr)
68	TCROP	720	0	0	720	240	Time crop surface is present (hr)
69	THARV	1800		720	1680		Harvest time (hrs)
70	YIELD1	2.5 x 10^7			2.5 x 10^7		Yield of tomatoes (g/ha)
71	YIELD2	2.5 x 10^7			2.5 x 10^7		Yield of zucchini (g/ha)
72	YIELD3	1 x 10^6			1 x 10^6		Yield of carrots (g/ha)
73	HAY		1.6	1.6			Grass present in field, or hay yield (kg/m^2)
74	PLNT1				0.4		Fraction of home garden in above-ground crop
75	PLNT2				0.3		Fraction of home garden in on-ground crop
76	PLNT3				0.3		Fraction of home garden in below-ground crop
77	PPG	--			--		Pathogen concentration on crop (paqthogens/g)
78	CATTLE		1	1			Type of cattle
79	COWS		12	12			Herd size
80	STORAG			720			Length of forage storage (days)
81	FORAG		7	7			Forage consumed per cow per day (kg)
82	ALFALF			30			Percent of feed which is harvested crop
83	SCNSMP		1.1	1.1			Soil consumed per cow per day (kg)
84	FATTEN			720			Number of hours cattle to be fed forage
85	TSLOTR		-2	-2			Time of slaughter (day)

#No default values, must be supplied by user
*Pathogen-specific, see Table A-2
**Practice- and crop-specific
--Calculated internally by the program

TABLE A-2

Pathogen-Specific Default Values

Position	Name	Pathogen	Default Value I	II	III	IV	V	Definition
12	MID	Salmonella	10	10	10	10	10	Minimum Infective Dose (Number of pathogens ingested)
		Ascaris	1	1	1	1	1	
		Enterovirus	1	1	1	1	1	
37	SLOPES	Salmonella	0.0206	0.0206	0.0206	0.0206	0.0206	Process function parameter used to calculate die-off of pathogens in soil as a function of temperature
		Ascaris						
		Enterovirus	0.00145	0.00145	0.00145	0.00145	0.00145	
38	NTRCPS	Salmonella	2.113	2.113	2.113	2.113	2.113	Process function parameter used to calculate die-off of pathogens in soil as a function of temperature
		Ascaris						
		Enterovirus	2.957	2.957	2.957	2.957	2.957	
39	SLOPEP	Salmonella	0.00449	0.00449	0.00449	0.00449	0.00449	Process function parameter used to calculate die-off of pathogens in particulates as a function of temperature
		Ascaris						
		Enterovirus						
40	NTRCPP	Salmonella	1.435	1.435	1.435	1.435	1.435	Process function parameter used to calculate die-off of pathogens in particulates as a function of temperature
		Ascaris						
		Enterovirus						
44	SUBSOL	Salmonella	5×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}	Transfer fraction: Soil surface to subsurface soil
		Ascaris	0	0	0	0	0	
		Enterovirus	0.001	0.001	0.001	0.001	0.001	
45	SUSPND	Salmonella	0.005	0.001	0.001	0.005	0.001	Transfer fraction: Soil surface to soil surface water
		Ascaris	0.01	0	0	0.01	0	
		Enterovirus	0.01	0.001	0.001	0.01	0.001	

TABLE A-2 (Continued)

Pathogen-Specific Default Values

			Default Value					
Position	Name	Pathogen	I	II	III	IV	V	Definition
53	FRGRND	Salmonella	0.001	0.001	0.001			Transfer fraction: **Subsurface soil to groundwater**
		Ascaris	0	0	0			
		Enterovirus	0.001	0.001	0.001			
54	SSWTCS	Salmonella		0.1	0.1		0.1	Transfer fraction: **Soil surface water to crop surface**
		Ascaris		0.05	0.05		0.05	
		Enterovirus		0.1	0.1		0.1	

TABLE A-3

Proposed Initial Value Menu for Pathogen Concentration Parameter, ASCRS

	Estimated Mean Organisms/kg (dry wt) of Material*		
Material	Salmonella	Ascaris	Viruses
Raw Liquid Municipal Sludge	5×10^5	5×10^3	5×10^5
Liquid Digested Sludge (Anaerobic)	5×10^4	5×10^3	1×10^5
Liquid Digested Sludge (Aerobic)	5×10^4	5×10^3	1×10^5
Dried Digested Sludge	1×10^3	5×10^2	1×10^4
Composted Sludge	1×10^6**	1×10^0	5×10^1
Sludge Amended Soil	2×10^3	1×10^0	3×10^3

*Adapted from Sorber and Moore, 1987

**Assumes regrowth as described by Yanco, 1988

TABLE A-4

Variables and Default Values for Subroutine RISK

Position	Name	Default Value	Definition
2	COOKA	1.E-5	Survival of Ascaris during cooking
3	COOKP	1.E-5	Survival of enterovirus during cooking
4	COOKS	1.E-30	Survival of Salmonella during cooking
5	DRECTC	0.1	Ingestion rate of crop surface from direct contact in g/day
6	DRECTS	0.1	Ingestion rate soil from direct contact in g soil/day
7	IBLAN	0	Flag for blanching of vegetables
8	ICAN	0	Flags canning sequence. If ICAN=1, the vegetable-exposure risk calculation will include the effects of storage of raw vegetable, washing, blanching, canning, storage of cans and cooking.
9	ICANG	0	Flag for vegetable canning alone
10	ICOOK	0	Flag for cooking of vegetables and meat
11	IFREE	0	Flags freezing sequence. If IFREE=1, the vegetable-exposure risk calculation will include the effects of storage of raw vegetable, washing, blanching freezing, frozen storage and cooking.
12	IFREG	0	Flag for vegetable freezing alone
13	IPAST	0	Flag for pasteurization of milk
14	ISTRH	1	Flag for storage of vegetables before processing. When ISTRH=1, the effects of storage on pathogen population are included in the vegetable-exposure risk calculation. When ISTRH=0, these effects are not included.

TABLE A-4 (Continued)

Variables and Default Values for Subroutine RISK

Position	Name	Default Value	Definition
15	ISTRP	0	Flag for storage of processed vegetables
16	IWASH	1	Flag for washing of vegetables
17	PASTB	1.E-9	Survival of Salmonella after pasteurization
18	PASTA	0.001	Survival of Ascaris after pasteurization
19	PASTP	0.001	Survival of enterovirus after pasteurization
20	TEMI2	4	Temperature (°C) of milk storage before pasteurization
21	TEMI4	4	Temperature (°C) of milk storage after pasteurization
22	TEMP2	7	Temperature (°C) of storage of vegetables before processing
23	TEMP4	0	Temperature (°C) of storage of frozen meat
24	TMIS2	24	Time (hours) of milk storage before pasteurization
25	TMIS4	24	Time (hours) of milk storage after pasteurization
26	TMP2M	4	Temperature (°C) of storage of meat after slaughter
27	TMP7F	-4	Temperature (°C) of storage of frozen foods
28	TMP7N	20	Temperature (°C) of storage of canned foods
29	TSTM2	720	Duration in hours of meat storage (unfrozen between slaughter and freezing)
30	TSTR2	168	Duration (hours) of vegetable storage before processing

TABLE A-4 (Continued)

Variables and Default Values for Subroutine RISK

Position	Name	Default Value	Definition
31	TSTR4	120	Time of storage of frozen meat
32	TSTR7	720	Duration of vegetable storage after processing
33	VOLPND	1.E2	Volume (m^3) of runoff pond
34	XDIST	200	Distance (in meters) downwind between particulate source and exposed individual
35	YDIST	0	Lateral distance (in meters) of human receptor from a line directly downwind of aerosol source

TABLE A-5

Variables and Default Values for Subroutine RAINS

Position	Name	Default Value	Function
2	PDUR	2	Duration of rainfall (hours)
3	PTOT	5.0	Total rainfall (cm)
4	BTLAG	0.5	Basin time lag (hr)
5	CN	80	Curve number
6	AMC	2	Antecedent moisture conditions
7	STAD	0.4	Storm advancement coefficient
8	USLEK	0.4	USLE K value (soil erodibility factor)
9	USLEL	3.0	USLE L value (slope length factor)
10	USLES	0.25	USLE S value (slope steepness factor)
11	USLEC	0.5	USLE C value (cover management factor)
12	USLEP	1.0	USLE P value (supporting practices)
13	PI	SUSPND	Pathogen suspension factor
14	WSOIL	1.33	Bulk density of soil (g/cm^3)

TABLE A-6

Variables and Default Values for Subroutine GRDWTR

Position	Name	Default Value	Function
	CA	FRGRND*N(8)	Initial number of organisms
2	V	3.6	Velocity of groundwater (cm/hr)
3	D	60	Dispersion coefficient (cm^2/hr)
4	R	1.0	Retardation coefficient
5	DZERO	0	Exponential growth rate
6	DONE	0	Exponential inactivation rate
7	DBND	0	Decaying input concentration
8	ALPHA	0.012	Exponential decay of input (per hr)
9	XI	50	Starting distance (m) from source
10	DX	50	Distance increment (m) in calculation
11	XM	50	Maximum distance (m) from source
12	DT	1	Time increment (hr) in calculation

APPENDIX B. OPERATIONS GUIDE

PATHOGEN RISK ASSESSMENT FOR LAND APPLICATION OF MUNICIPAL SLUDGE: COMPUTER MODEL OPERATIONS GUIDE
VERSION 3.1, OCT. 1989

** WARNING **
THIS PROGRAM REQUIRES AT LEAST 540K FREE RAM.

** WARNING **
YOUR CONFIG.SYS FILE MUST BE WRITTEN
TO ALLOW AT LEAST 20 OPEN FILES.
The system default configuration may be 8 simultaneously openfiles.
If so, the program will crash, and it will be necessary to
use a text editor or line editor to add the line
FILES=20 to CONFIG.SYS, and then re-boot the computer.

This program does not require a math coprocessor, but it will run significantly faster if one is present.

In this operations guide, file names will be printed in UNDERLINED CAPITALS. Prompts written by the program to the monitor screen will be printed in CAPITALS. The user's responses will be printed in **BOLD CAPITALS**, and responses for which the user must choose a variable or file name are enclosed in <ANGLE BRACKETS>. Function keys will be identified by parentheses (ENTER), (CONTROL). In some cases responses will be identified by equation numbers (flush right).

This program requires input information to specify over 100 variables and usage options. Some of these data must be entered in response to prompts that will appear on the screen of your monitor. Others have default values written into the program. You will be given the opportunity to change the values of these variables during the input phase of the program. Default values are listed in Appendix A, Tables A-1 through A-6 of Pathogen Risk Assessment for Land Application of Municipal Sludge, both Volume I: Methodology and Computer Model and Volume II: User's Manual, and in Tables A-7 through A-12 of the User's Manual; tables A-1 through A-6 are identical in both documents. More details about the variables can be found in the User's Manual.

1. GETTING STARTED

Because the program is too large to fit on a low-density floppy disk, it has been compressed. To install the program, insert the program disk in drive A and type **A:\INSTALL (ENTER)**. A batch file on the program disk will create a directory named \RISKMOD on drive C and expand the program as it is copied to that directory. A procedure for testing the program is described below in Section 4. INPUT FILES. The output files should match those in the appendix to this guide.

Gather any information you have that is relevant to the specific case you intend to model. This information will include the concentration of pathogens in the sludge (organisms/kg dry wt), size of the area to be considered, frequency and depth of rainfall, etc. You must enter:

NAME OF OUTPUT FILE
LENGTH OF MODEL RUN
P(1) ASCRS
P(35) TMAX
P(36) TMIN

The following P-variables should be changed to reflect the characteristics of the particular situation you want to model:

Site-specific values

2	APRATE
7	AREA
9	AQUIFR
10	POROS
11	FILTR8

Environmental values

13	TRAIN
23	TWIND
24	DWIND
25	WINDSP
32	BREEZE

Practice-specific values

6	APMETH	68	TCROP
17	IRMETH	69	THARV
18	DILIRR	74	PLNT1
19	NIRRIG	75	PLNT2
20	IRRATE	76	PLNT3
21	DEPTH	78	CATTLE
30	COVER	79	COWS
66	CROP	80	STORAG
67	TCULT	84	FATTEN
		85	TSLOTR

Be sure that you are in the directory containing the program or that the computer's PATH statement includes that directory. It is not necessary to have a printer attached to the computer doing the model runs or to print the results immediately. However, if the output file is to be printed later, either from the same computer or from a disk file, be sure that the output file name (1-1) is different for each model run.

You will be asked to respond with values of input variables at several points at the beginning of the program. After each response press the (ENTER) or (RETURN) key.

To begin the model run, enter

RISK

1.1. OUTPUT FILE

After printing a title page, the monitor screen will respond

DO YOU WANT TO ENTER VALUES FROM
THE KEYBOARD OR FROM A FILE?
(ENTER "K" OR "F")

If your response is **F**, you will be prompted:

ENTER THE NAME OF THE INPUT FILE.

Enter the name of the input file, which contains the parameters required for that sample run. (A sample input file is included below in Section 4.) The screen output described in the remainder of Section 1 will scroll past, but you will not need to respond to the prompts.

If your response is **K**, you will be prompted:

```
ENTER A NAME FOR THE OUTPUT FILE.
YOU MAY USE UP TO 8 CHARACTERS.
```

Enter the filename

<FILENAME> (1-1)

You must supply the filename. Otherwise, the program will not continue.

1.2. TIME PARAMETERS

You must specify the time parameters for your model run. There are no default values for these parameters. For practices that involve a harvested crop, it is likely that the model run will be longer than the time required to grow the crop to harvesting, but shorter model runs to determine immediate effects of sludge application are also possible and appropriate.

You will be prompted on the monitor screen:

```
*** SLUDGE PATHOGEN MODEL ***

ENTER VALUES FOR THE FOLLOWING
(PRESS RETURN AFTER EACH):

1. END TIME OF PRACTICE IN DAYS
```

Enter the number of days you want in the model run, e.g.,

20.

```
2. PRINTING SAMPLE RATE IN HOURS
```

The number of pathogens in each compartment at the time interval specified by this response will be printed in a file named PATHOUT. This file is useful if you want to see the pathogen number in each compartment at the specified time interval. Otherwise, any number will do, and large numbers (e.g., 24) will make for smaller files on your hard disk.

1.3. MODEL SLUDGE USE PRACTICE

You must choose which of the sludge application practices you want to model. These practices are described in the descriptive document Pathogen Risk Assessment for Land Application of Municipal Sludge: Volume I: Methodology and Computer Model. There is no default value for this entry.

You will be prompted on the monitor screen:

```
PROVIDE PRACTICE NUMBER
YOUR CHOICES ARE:
    1   APPLICATION OF LIQUID SLUDGE FOR PRODUCTION
        OF COMMERCIAL CROPS FOR HUMAN CONSUMPTION

    2   APPLICATION OF LIQUID SLUDGE TO
        GRAZED PASTURE

    3   APPLICATION OF LIQUID SLUDGE FOR PRODUCTION
        OF CROPS PROCESSED FOR ANIMAL CONSUMPTION

    4   APPLICATION OF DRIED OR COMPOSTED SLUDGE
        TO RESIDENTIAL GARDENS

    5   APPLICATION OF DRIED OR COMPOSTED SLUDGE
        TO RESIDENTIAL LAWNS
```

Enter the appropriate number.

1.4. PATHOGEN TYPE AND INITIAL POPULATIONS IN COMPARTMENTS

You must choose the type of pathogen for the model run. Only one pathogen type can be modeled during each model run. There is no default value for this entry.

You will be prompted on the monitor screen:

```
PROVIDE PATHOGEN TYPE

YOUR CHOICES ARE:
    1   SALMONELLA      (BACTERIA)
    2   ASCARIS         (PARASITE)
    3   ENTEROVIRUS     (VIRUS)
```

Enter **1**, **2**, or **3**.

The monitor screen will respond:

THE VARIABLES LISTED BELOW MAY BE OPTIONALLY CHANGED FROM THEIR DEFAULT VALUES: (1-2)

POPL(1-22) (INITIAL PATHOGEN POPULATIONS
OF COMPARTMENTS IN PRACTICE.
[SEE MANUAL FOR DESCRIPTIONS.]
DEFAULT=0.0)

1. TYPE THE NUMBER "1" TO ACCEPT THE CURRENT VALUES AND CONTINUE WITH THE PROGRAM.
2. TYPE THE NUMBER "2" IF YOU WISH TO LOAD A PATHOGEN POPULATION INTO A COMPARTMENT.

Enter **1** to accept the default condition, which starts the model with no pathogens in any compartment. To simulate a starting condition in which some compartments have an initial pathogen load, enter **2**. You will be prompted:

PROVIDE POPL SUBSCRIPT IN THE RANGE OF 1-22.

Enter the number of the compartment you want to modify. The monitor screen will respond:

PROVIDE NEW VALUE OF THIS POPULATION.

Enter the appropriate number. The program will loop back to the prompt at line (1-2), allowing you to alter each compartment until you respond with 1, indicating that you are satisfied with the initial states of the compartments.

1.5. INITIAL PATHOGEN CONCENTRATION IN SLUDGE

You must provide the initial concentration of pathogens in the sludge to be applied. There is no default value for this entry.

You will be prompted on the monitor screen:

PROVIDE SLUDGE PATHOGEN DENSITY (NUMBER OF PATHOGENS
PER KILOGRAM (DRY WEIGHT) OF APPLIED SLUDGE)

ENTER A FORM SUCH AS 100000 OR 1E5

Enter the concentration of pathogens of the kind you specified. The concentration must be in the units of number per kg dry weight, and in either typed-out or scientific notation form. Do not use commas or spaces. If you do not know the concentration of pathogens in the sludge, you can use the typical values taken from Table A-3. However, the results will be more useful if values descriptive of the specific sludge batch are entered.

1.6. PATHOGEN REDUCTION REQUIREMENTS

U.S. EPA Pathogen Reduction Requirements require a waiting period between sludge application and land use. The waiting period depends on both the class of sludge treatment and the type of land use. For a description of sludge treatment classes, see Section 4.3 of the User's Manual. To establish these waiting periods, you will be asked to enter the time at which sludge application ends:

```
WHEN DOES SLUDGE APPLICATION CEASE (DAYS)?
 (FOR A SINGLE APPLICATION, ENTER "0".)
```

Enter the appropriate number. If the option of irrigating with liquid sludge is to be used, enter the day on which the use of sludge as irrigation water will be ended. The monitor will next respond:

```
LAND ACCESS RESTRICTIONS VARY WITH THE CLASS
  OF SEWAGE TREATMENT.  WHAT CLASS APPLIES TO
  THIS MODEL RUN? (ENTER A, B OR C).
```

Enter the appropriate letter.

1.7. ANNUAL TEMPERATURE CYCLE

Because die-off rates are dependent on ambient temperature, the model uses an annual air temperature cycle in calculations of process functions. The calculated air temperature during the model run depends on the time of year and the extremes of monthly average air temperature at the location being modeled. (For details see the User's Manual, Section 4.4). To obtain the necessary data for these calculations, the program will prompt you:

```
WHEN DOES THE PRACTICE BEGIN?
     MONTH (1-12):

     DAY (1-31):
```

Enter the number of the month and the day. You will then be prompted:

```
WHAT IS THE LOCAL AIR TEMPERATURE RANGE?

     JANUARY AVERAGE AIR TEMP. (DEG C):
     JULY AVERAGE AIR TEMP. (DEG C):
```

Enter the monthly average temperatures for these months to serve as minimum and maximum temperatures for the temperature cycle calculation. Average minimum and maximum temperatures at several locations in the United States can be found in Table A-9 of Volume II: User's Manual. In this table, temperatures for January and July are given in °C as well as in °F.

1.8. MODEL VARIABLES

The majority of the variables used by the program are specified at this step. These variables provide the operating conditions for most of the model calculations, so they should be chosen to describe as accurately as possible the conditions you want to model.

You will be prompted on the monitor screen:

```
THE DEFAULT VALUES FOR MODEL PARAMETERS                (1-3)
DEPEND ON THE PRACTICE AND PATHOGEN CHOSEN.

YOU HAVE CHOSEN PRACTICE              1
 AND PATHOGEN      1   SALMONELLA
PRESS RETURN TO CONTINUE


THE CURRENT VALUES ARE:

POSITION     VARIABLE    CURRENT VALUE      CHANGED
                                            BY USER
--------     --------    -------------
    1        ASCRS        1.00000E+12
    2        APRATE        10000.
    3        ASCIN         .00000
    4        TREG          .00000
    5        UPLIM        1.00000E+09
    6        APMETH        1.0000
    7        AREA          10.000
    8        TEMP          .00000
    9        AQUIFR        10.000
   10        POROS         .30000
   11        FILTR8        2.0000
   12        MID           10.000
   13        TRAIN        -2.0000
   14        RDEPTH        5.0000
   15        TK            .00000
   16        TIRRG         .00000
   17        IRMETH        .00000
   18        DILIRR        .00000
   19        NIRRIG        2.0000
   20        IRRATE        .50000
PRESS RETURN TO CONTINUE
```

```
POSITION     VARIABLE     CURRENT VALUE        CHANGED
________     ________     _____________        BY USER

  21         DEPTH           2.5000
  22         COUNT           .00000
  23         TWIND           60.000
  24         DWIND           6.0000
  25         WINDSP          18.000
  26         EPSMLT          .33000
  27         ESILT           .40000
  28         EHT             2.0000
  29         SCRIT           7.5000
  30         COVER           .00000
  31         AEREFF          1.00000E-03
  32         BREEZE          4.0000
  33         HT              1.6000
  34         ANDAY           345.00
  35         TMAX            30.000
  36         TMIN            .00000
  37         SLOPES          2.06000E-02
  38         NTRCPS          2.1130
  39         SLOPEP          4.49000E-03
  40         NTRCPP          1.4350
PRESS RETURN TO CONTINUE

POSITION     VARIABLE     CURRENT VALUE        CHANGED
________     ________     _____________        BY USER

  41         ASLSUR          .90000
  42         FSSUR           1.0000
  43         FRRAIN          .00000
  44         SUBSOL          5.00000E-04
  45         SUSPND          5.00000E-03
  46         FCROP1          1.00000E-08
  47         FCROP2          6.00000E-03
  48         FCROP3          1.00000E-03
  49         FCROP4          1.00000E-04
  50         FCROP5          1.20000E-02
  51         FCROP6          .00000
  52         FCROP7          2.00000E-04
  53         FRGRND          1.00000E-03
  54         SSWTCS          .00000
  55         PSTMG           .00000
  56         CSTSS           .00000
  57         SSTCS           .00000
  58         CSTSSW          .75000
  59         DTCTMT          .00000
  60         DTCTMK          .00000
PRESS RETURN TO CONTINUE
```

```
POSITION    VARIABLE    CURRENT VALUE      CHANGED
________    ________    _____________      BY USER

   61        TMTSS         .00000
   62        TMTH          .00000
   63        TMTU          .00000
   64        HTM           .00000
   65        UTM           .00000
   66        CROP          1.0000
   67        TCULT        -2.0000
   68        TCROP         720.00
   69        THARV         1800.0
   70        YIELD1       2.50000E+07
   71        YIELD2       2.50000E+07
   72        YIELD3       1.00000E+06
   73        HAY           .00000
   74        PLNT1         .00000
   75        PLNT2         .00000
   76        PLNT3         .00000
   77        PPG           .00000
   78        CATTLE        .00000
   79        COWS          .00000
   80        STORAG        .00000
PRESS RETURN TO CONTINUE

POSITION    VARIABLE    CURRENT VALUE      CHANGED
________    ________    _____________      BY USER

   81        FORAG         .00000
   82        ALFALF        .00000
   83        SCNSMP        .00000
   84        FATTEN        .00000
   85        TSLOTR        .00000
PRESS RETURN TO CONTINUE

1. TYPE THE NUMBER "1" IF YOU WISH TO ACCEPT THE
   CURRENT VALUES AND CONTINUE WITH THE PROGRAM.

2. PROVIDE P SUBSCRIPT IN THE RANGE OF 2-85
   IF YOU WISH TO CHANGE A PARAMETER OF THE MODEL.

   TYPE "99" IF YOU NEED TO SEE THE LIST AGAIN
```

Variables are described in the User's Manual. Default values for the variables in each practice are listed in Tables A-1 and A-2. To accept all of the default values, enter 1. To change any of these values, enter the number of the variable to be changed (given under the heading Position in the table). Except for variable 13 (RAINS), you will be prompted:

```
PROVIDE NEW VALUE OF THIS P.
```

Enter the appropriate number. The program will then loop back to (1-3) until you enter 1, indicating that you are satisfied with the values of the model variables. Except for variable 13, each time the sequence starting at (1-3) is printed, the new value will be printed at the appropriate location, and an asterisk will appear in the column labeled CHANGED BY USER.

1.9. RAINFALL

If you entered 13 to include rainfall in the model run, <u>SUBROUTINE RAINS</u> will be called, and tne prompt will be:

```
GIVE THE NUMBER OF RAIN EVENTS (BETWEEN 1 & 10)
```

Enter the appropriate number. The monitor will respond:

```
GIVE START TIME (IN HRS) OF RAIN EVENT NO. 1                (1-4)
```

Enter the starting time of the first rainfall. Time is measured from the beginning of the model run (time=0 at the beginning of sludge application in Compartment I), so a starting time of 246 hours would call for rain on the 11th day. The monitor will respond:

```
RAIN NO.  1 AT ##.## (HRS)                                   (1-5)
THE PARAMETERS FOR PATHOGEN TRANSPORT BY SURFACE WATER
MAY BE OPTIONALLY CHANGED FROM THEIR DEFAULT VALUES:

NUMBER      PARAMETER      CURRENT  VALUE
  2          PDUR             2.00
  3          PTOT             5.00
  4          BTLAG             .50
  5          CN              80.00
  6          AMC              2.00
  7          STAD              .40
  8          USLEK             .40
  9          USLEL            3.00
 10          USLES             .25
 11          USLEC             .50
 12          USLEP            1.00
 13          PI                .00
 14          WSOIL            1.33
PRESS RETURN TO CONTINUE

1. TYPE "1" TO ACCEPT THE CURRENT VALUES
   FOR RAIN NO.  1 AND PROCEED TO NEXT RAIN.

2. TYPE THE NUMBER ("2"-"14") CORRESPONDING TO THE
   PARAMETER THAT YOU WANT TO CHANGE.
```

Default values for these parameters are listed in Table A-5 and explained in Section 5.3 of Volume II: User's Manual. If you wish to change any of the parameters from their default values, enter the appropriate variable number. You will be prompted to enter a new value for the variable. The program will then loop back to (1-5) until you enter 1, indicating that you are satisfied with the values of the surface runoff and sediment transport parameters for that rainfall. The monitor will respond:

```
ARE YOU DONE WITH RAIN NO.  1 ? (Y/N)
```

If you have made a mistake or want to change a variable enter N, and the program will loop back to (1-5). If you are satisfied with the values of the variables for that rainfall, enter Y to proceed. The program will loop back to (1-4) for each additional rainfall you specified ("RAIN EVENT NO. 2", "RAIN EVENT NO. 3", etc.), and then back to (1-3) until you enter 1, indicating that you are satisfied with the values of the variables. The response will be:

```
CURRENT VALUES ACCEPTED
```

1.10. OPTIONAL PROCESS FUNCTIONS

Process functions (growth or inactivation rates) are included in the program as defaults. Default inactivation rates for Salmonella, Ascaris and enterovirus in moist soil and Salmonella in dry particulates are temperature dependent, whereas inactivation rates of Salmonella, Ascaris and enterovirus in water and in aerosols are variables whose defaults are listed in Table A-12 (for more information see Volume II: User's Manual, Section 4.4).

You will see:

```
OPTIONAL GROWTH OR INACTIVATION RATES MAY BE ENTERED
TO REPLACE THE DEFAULT VALUES (SEE THE USER MANUAL
FOR A DESCRIPTION OF THE DEFAULT CONDITIONS).

  1. ACCEPT VALUES

                                   CURRENT VALUE

  2. PROC1 - MOIST SOIL             -5.000000

  3. PROC2 - DRY PARTICULATES       -5.000000

  4. PROC3 - WATER SUSPENSION       -5.000000

  5. HCRIT - DROPLET AEROSOL        -2.800000E-02

IF YOU WISH TO CHANGE THE VALUE OF A VARIABLE, ENTER
THE NUMBER.  TO ACCEPT THE CURRENT VALUES, ENTER "1".
```

You may choose growth or inactivation rates that will override the default conditions for these variables. Except for aerosols, rates should be entered as the logarithm (base 10) of the fractional survival or growth after one hour (e.g., an inactivation rate resulting in 10% survival after one hour would be entered as -1). For aerosols (HCRIT), the rate should be entered as the logarithm of fractional survival after 1 minute.

DO NOT ENTER -5. This is the internal flag setting indicating that default conditions are to be used. You may use -5.0001 or -4.9999 or any other number close to -5. The monitor will respond:

```
CURRENT VALUES ACCEPTED.
```

1.11. INFECTION RISK PARAMETERS

Infection risk parameters are used in the exposure calculations. Most have to do with food processing and storage, but variables 4 and 5 describe soil and crop ingestion, and 31-34 are physical parameters for pond size and for exposure to particulate and liquid aerosols.

You will be prompted on the monitor screen:

```
THE INFECTION RISK PARAMETERS LISTED BELOW MAY BE    (1-6)
OPTIONALLY CHANGED FROM THEIR DEFAULT VALUES.

NUMBER  PARAMETER  VALUE     NUMBER  PARAMETER   VALUE
  2     COOKA       .000       19    PASTP        .001
  3     COOKP       .000       20    TEMI2       4.000
  4     COOKS       .000       21    TEMI4       4.000
  5     DRECTC      .100       22    TEMP2       7.000
  6     DRECTS      .100       23    TEMP4        .000
  7     IBLAN       .000       24    TMIS2      24.000
  8     ICAN        .000       25    TMIS4      24.000
  9     ICANG       .000       26    TMP2M       4.000
 10     ICOOK       .000       27    TMP7F      -4.000
 11     IFREE       .000       28    TMP7N      20.000
 12     IFREG       .000       29    TSTM2     720.000
 13     IPAST       .000       30    TSTR2     168.000
 14     ISTRH      1.000       31    TSTR4     120.000
 15     ISTRP       .000       32    TSTR7     720.000
 16     IWASH      1.000       33    VOLPND    100.000
 17     PASTB       .000       34    XDIST     200.000
 18     PASTA       .001       35    YDIST        .000
PRESS RETURN TO CONTINUE

1. TYPE "1" TO ACCEPT THE CURRENT VALUES
   AND CONTINUE WITH THE PROGRAM.

2. TYPE THE NUMBER ("2" - "35") CORRESPONDING TO
   THE PARAMETER THAT YOU WISH TO CHANGE.
```

Default values and definitions for these parameters are listed in Table A-4. If you wish to change any of the parameters from their default values, enter the appropriate variable number. You will be prompted to enter a new value for the variable. The program will then loop back to (1-6), printing new values of variables, until you enter 1, indicating that you are satisfied with the values of the risk parameters. The monitor will then display a summary of the initial conditions chosen for the model run.

1.12. SUBSURFACE TRANSPORT FOLLOWING RAINFALL AND IRRIGATION

You may specify values of the variables used in subsurface transport calculations.

You will be prompted on the monitor screen:

```
THE PARAMETERS FOR PREDICTING VIRAL AND BACTERIAL   (1-7)
TRANSPORT IN GROUNDWATER AFTER LAND APPLICATION OF
SEWAGE SLUDGE MAY BE OPTIONALLY CHANGED FROM THEIR
DEFAULT VALUES.

NUMBER    PARAMETER     CURRENT VALUE
   2        V                3.600
   3        D               60.000
   4        R                1.000
   5        DZERO             .000
   6        DONE              .000
   7        DBND              .000
   8        ALPHA             .012
   9        XI              50.000
  10        DX              50.000
  11        XM              50.000
  12        DT               1.000
PRESS RETURN TO CONTINUE

1. TYPE "1" TO ACCEPT THE CURRENT VALUES.

2. TYPE THE NUMBER ("2"-"12") CORRESPONDING TO THE
   PARAMETER THAT YOU WANT TO CHANGE.
```

Definitions and default values for these parameters are listed in Table A-6 and described in Section 5.4 of Volume II: User's Manual. If you wish to change any of the parameters from their default values, enter the appropriate variable number. You will be prompted to enter a new value for the variable. The program will then loop back to (1-7), printing the new values, until you enter 1, indicating that you are satisfied with the values of the subsurface transport parameters.

2. RUNNING

When the computations begin, the following messages will appear on the screen: At the first iteration of Practices 1, 2 and 3,

```
          RUNNING . . .

                _______________PROBABILITY OF INFECTION_______________
DAY       ONSITE         OFFSITE       EATER         DRINKER       SWIMMER
```

of Practice 4,

```
          RUNNING . . .

                ____PROBABILITY OF INFECTION____
DAY             ONSITE           OFFSITE        EATER
```

or of Practice 5,

```
          RUNNING . . .

              PROBABILITY OF INFECTION
DAY             ONSITE           OFFSITE
```

After each day's simulation, the number of the day and the probability of infection for the day will be printed on the screen. After every 20 days' simulation the headings will be printed again. A copy of this output will appear in the file specified at the beginning of the model run.

Whenever the subsurface transport subroutine is called, there will be a delay in printing the output data. This first occurs during day 2 under most circumstances. If the computer does not have a math coprocessor, the delay may be as much as 15 seconds per day of the model run, so don't be alarmed if nothing seems to be happening.

The model will run until the day specified unless the number of pathogens in each compartment falls to 0, in which case the program will be terminated to save computation time. The response on the monitor will be:

```
          RUN TERMINATED BECAUSE ALL COMPARTMENTS = 0
```

At the end of the model run, the monitor will respond:

```
          . . . RUN COMPLETE.
```

3. RECOVERING THE DATA

After the run has been completed, you will see the reminder,

```
YOU WILL FIND THE INFECTION PROBABILITY OUTPUT FROM
THIS RUN IN THE FILE YOU SPECIFIED.
```

To view the results, you can use a word processor or text editor, or use the TYPE command:

```
TYPE <FILENAME>.
```

The file will then scroll up the monitor screen. You can stop its progress by typing (CONTROL)S. It will start again if you strike any key.

To print the results, use the print functions of a word processor or text editor, or type (CONTROL)P to activate the printer echo mode of your computer, and then

```
TYPE <FILENAME>.
```

The file should then be printed. This file contains the probability of infection for each day. The contents of other files are summarized below.

File Name	Description
User Provides	Contains a summary of input values and the risk of infection for each 24 hour period. The name of the file is provided by the user at the second prompt after invoking the model.
EXOUT	Output from the groundwater transport routine. Contains the parameters used by the subroutine and the composite contents of the output compartment at each specified distance increment and for each time interval during the model run.
PATHOUT	Contains the number of pathogens in each compartment at the time interval specified by the user.
RAINS	Output from the RAINS subroutine.

4. INPUT FILES

The model can be run by use of an input file in place of interactive keyboard responses to prompts. An input file can be created by using a word processor or line editor to enter all of the appropriate responses in sequence. This file is saved under a file name (INPUT.IN for this example). The input file on the distribution disk contains several unrealistic values; however, these values were chosen to allow a larger number of positive results in the short time of the test model run.

During interactive keyboard operation blank lines are entered in response to the prompt PRESS RETURN TO CONTINUE. With an input file, however, there must be a character on the line containing that return. In this example, that dummy character is X. Any character string of up to four characters can be used. The values in this file are:

TEST	(Title)
20	(Length of run)
8	(Print sample rate)
1	(Practice number)
1	(Pathogen type)
1	(Initial compartment populations)
1E12	(Pathogen concentration)
0	(Day sludge application ends)
A	(Class of sludge treatment)
4	(Month model begins)
1	(Day model begins)
0	(Minimum average temperature)
30	(Maximum average temperature)
X	(Dummy character to continue (1))
X	(Dummy character to continue (2))
X	(Dummy character to continue (3))
X	(Dummy character to continue (4))
X	(Dummy character to continue (5))
X	(Dummy character to continue (6))
68	(P-value for TCROP)
140	(New value for TCROP)
X	(Dummy character to continue (1))
X	(Dummy character to continue (2))
X	(Dummy character to continue (3))
X	(Dummy character to continue (4))
X	(Dummy character to continue (5))
X	(Dummy character to continue (6))
69	(P-value for THARV)
180	(New value for THARV)
X	(Dummy character to continue (1))
X	(Dummy character to continue (2))
X	(Dummy character to continue (3))
X	(Dummy character to continue (4))
X	(Dummy character to continue (5))
X	(Dummy character to continue (6))
13	(P-value for rainfall)
1	(Number of rainfalls)
120	(Time at which rain begins)

```
X            (Dummy character to continue)
1            (Accept default values)
Y            (Confirm rainfall values)
X            (Dummy character to continue (1))
X            (Dummy character to continue (2))
X            (Dummy character to continue (3))
X            (Dummy character to continue (4))
X            (Dummy character to continue (5))
X            (Dummy character to continue (6))
1            (Accept optional P-variables)
1            (Accept die-off rate parameters).
X            (Dummy character to continue)
1            (Accept default risk variables)
X            (Dummy character to continue)
X            (Dummy character to continue)
9            (Position of variable XI)
12           (New value for XI)
X            (Dummy character to continue)
10           (Position of variable DX)
1            (New value for DX)
X            (Dummy character to continue)
11           (Position of variable XM)
12           (New value for XM)
X            (Dummy character to continue)
1            (Accept current variables)
```

The model run is begun by entering

```
RISK
F
INPUT.IN
```

The input data will automatically be supplied to the program from the input file.

If a number of successive runs are to be made, they may best be invoked from a batch file. In this case, if you want to see the PATHOUT and EXOUT files, use the batch file to rename them before the next run is invoked. For example, a batch file to run the model three times, using input files and saving the PATHOUT and EXOUT files might be:

```
RISK < RISK1.BAT
RENAME PATHOUT PATHOUT1
RENAME EXOUT EXOUT1
RISK < RISK2.BAT
RENAME PATHOUT PATHOUT2
RENAME EXOUT EXOUT2
RISK < RISK3 .BAT
RENAME PATHOUT PATHOUT3
RENAME EXOUT EXOUT3
```

where RISK1.BAT, RISK2.BAT and RISK3.BAT are batch files of the form

```
F
INPUT1.IN.
```

The intermediate batch files (RISK1.BAT, etc.) are small enough not to exceed the size limit for redirected standard input. The INPUTn.IN files supply the specific information for each model run as described in the sample input file.

5. SAMPLE OUTPUT

The output file from the test run described above should look like the following:

```
*******************************************************************************

TEST

*******************************************************************************


  PRACTICE STOP TIME=        20 DAYS
  PRINT SAMPLING RATE - IPRNT =      8 HOURS
  PRACTICE NUMBER =    1
  PATHOGEN =   1 SALMONELLA
  NUMBER OF COMPARTMENTS THIS PRACTICE =   16
  INITIAL POPULATIONS FOR COMPARTMENTS:
       COMPARTMENT   1 =   0.0000E+00
       COMPARTMENT   2 =   0.0000E+00
       COMPARTMENT   3 =   0.0000E+00
       COMPARTMENT   4 =   0.0000E+00
       COMPARTMENT   5 =   0.0000E+00
       COMPARTMENT   6 =   0.0000E+00
       COMPARTMENT   7 =   0.0000E+00
       COMPARTMENT   8 =   0.0000E+00
       COMPARTMENT   9 =   0.0000E+00
       COMPARTMENT  10 =   0.0000E+00
       COMPARTMENT  11 =   0.0000E+00
       COMPARTMENT  12 =   0.0000E+00
       COMPARTMENT  13 =   0.0000E+00
       COMPARTMENT  14 =   0.0000E+00
       COMPARTMENT  15 =   0.0000E+00
       COMPARTMENT  16 =   0.0000E+00
  SLUDGE PATHOGEN DENSITY =     1.0000E+12 NUMBER/KG


RAIN EVENT NO.  1    STARTING AT 120.00  HRS
```

```
THESE RESULTS ARE BASED ON THE FOLLOWING INPUT PARAMETERS

PRACTICE:          1
PATHOGEN:      1   SALMONELLA

THE DEFAULT VALUES AND THOSE CHANGED BY THE USER ARE
LISTED BELOW.

     POSITION     VARIABLE     ACCEPTED VALUE      CHANGED
                                                   BY USER
     ________     ________     ______________
        1         ASCRS         1.00000E+12
        2         APRATE          10000.
        3         ASCIN           .00000
        4         TREG            .00000
        5         UPLIM         1.00000E+09
        6         APMETH          1.0000
        7         AREA            10.000
        8         TEMP            .00000
        9         AQUIFR          10.000
       10         POROS           .30000
       11         FILTR8          2.0000
       12         MID             10.000
       13         TRAIN          -2.0000              *
       14         RDEPTH          5.0000
       15         TK              .00000
       16         TIRRG           .00000
       17         IRMETH          .00000
       18         DILIRR          .00000
       19         NIRRIG          2.0000
       20         IRRATE          .50000
       21         DEPTH           2.5000
       22         COUNT           .00000
       23         TWIND           60.000
       24         DWIND           6.0000
       25         WINDSP          18.000
       26         EPSMLT          .33000
       27         ESILT           .40000
       28         EHT             2.0000
       29         SCRIT           7.5000
       30         COVER           .00000
       31         AEREFF        1.00000E-03
       32         BREEZE          4.0000
       33         HT              1.6000
       34         ANDAY           345.00
       35         TMAX            30.000
       36         TMIN            .00000
       37         SLOPES        2.06000E-02
       38         NTRCPS          2.1130
       39         SLOPEP        4.49000E-03
       40         NTRCPP          1.4350
       41         ASLSUR          .90000
       42         FSSUR           1.0000
```

43	FRRAIN	.00000	
44	SUBSOL	5.00000E-04	
45	SUSPND	5.00000E-03	
46	FCROP1	1.00000E-08	
47	FCROP2	6.00000E-03	
48	FCROP3	1.00000E-03	
49	FCROP4	1.00000E-04	
50	FCROP5	1.20000E-02	
51	FCROP6	.00000	
52	FCROP7	2.00000E-04	
53	FRGRND	1.00000E-03	
54	SSWTCS	.00000	
55	PSTMG	.00000	
56	CSTSS	.00000	
57	SSTCS	.00000	
58	CSTSSW	.75000	
59	DTCTMT	.00000	
60	DTCTMK	.00000	
61	TMTSS	.00000	
62	TMTH	.00000	
63	TMTU	.00000	
64	HTM	.00000	
65	UTM	.00000	
66	CROP	1.0000	
67	TCULT	-2.0000	
68	TCROP	140.00	*
69	THARV	180.00	*
70	YIELD1	2.50000E+07	
71	YIELD2	2.50000E+07	
72	YIELD3	1.00000E+06	
73	HAY	.00000	
74	PLNT1	.00000	
75	PLNT2	.00000	
76	PLNT3	.00000	
77	PPG	.00000	
78	CATTLE	.00000	
79	COWS	.00000	
80	STORAG	.00000	
81	FORAG	.00000	
82	ALFALF	.00000	
83	SCNSMP	.00000	
84	FATTEN	.00000	
85	TSLOTR	.00000	

PROCESS VARIABLES FOR DIE-OFF OF PATHOGENS

VARIABLE	VALUE
PROC1 - MOIST SOIL	-5.000000
PROC2 - DRY PARTICULATES	-5.000000
PROC3 - WATER SUSPENSION	-5.000000
HCRIT - DROPLET AEROSOL	-2.800000E-02

THE INFECTION RISK PARAMETERS USED
IN THIS MODEL RUN ARE:

NUMBER	PARAMETER	VALUE	NUMBER	PARAMETER	VALUE
2	COOKA	.000	19	PASTP	.001
3	COOKP	.000	20	TEMI2	4.000
4	COOKS	.000	21	TEMI4	4.000
5	DRECTC	.100	22	TEMP2	7.000
6	DRECTS	.100	23	TEMP4	.000
7	IBLAN	.000	24	TMIS2	24.000
8	ICAN	.000	25	TMIS4	24.000
9	ICANG	.000	26	TMP2M	4.000
10	ICOOK	.000	27	TMP7F	-4.000
11	IFREE	.000	28	TMP7N	20.000
12	IFREG	.000	29	TSTM2	720.000
13	IPAST	.000	30	TSTR2	168.000
14	ISTRH	1.000	31	TSTR4	120.000
15	ISTRP	.000	32	TSTR7	720.000
16	IWASH	1.000	33	VOLPND	100.000
17	PASTB	.000	34	XDIST	200.000
18	PASTA	.001	35	YDIST	.000

THE PARAMETERS CHOSEN FOR GROUNDWATER TRANSPORT ARE:

NUMBER	PARAMETER	VALUE
2	V	3.600
3	D	60.000
4	R	1.000
5	DZERO	.000
6	DONE	.000
7	DBND	.000
8	ALPHA	.012
9	XI	12.000
10	DX	1.000
11	XM	12.000
12	DT	1.000

	PROBABILITY OF INFECTION				
DAY	ONSITE	OFFSITE	EATER	DRINKER	SWIMMER
1	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
2	1.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
3	1.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
4	1.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
5	1.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
6	1.000E+00	0.000E+00	0.000E+00	0.000E+00	1.000E+00
7	1.000E+00	0.000E+00	0.000E+00	0.000E+00	1.000E+00
8	1.000E+00	0.000E+00	0.000E+00	0.000E+00	1.000E+00
9	1.000E+00	0.000E+00	3.363E-04	2.220E-16	1.000E+00
10	1.000E+00	0.000E+00	0.000E+00	0.000E+00	1.000E+00
11	9.889E-01	0.000E+00	0.000E+00	0.000E+00	1.000E+00
12	3.994E-02	0.000E+00	0.000E+00	0.000E+00	1.000E+00
13	2.885E-06	0.000E+00	0.000E+00	7.183E-14	1.000E+00
14	1.677E-11	0.000E+00	0.000E+00	1.093E-11	1.000E+00
15	2.220E-11	0.000E+00	0.000E+00	1.079E-10	1.000E+00
16	1.110E-16	0.000E+00	0.000E+00	1.305E-10	1.000E+00
17	0.000E+00	0.000E+00	0.000E+00	3.828E-11	1.000E+00
18	0.000E+00	0.000E+00	0.000E+00	6.130E-12	1.000E+00
19	0.000E+00	0.000E+00	0.000E+00	1.208E-12	1.000E+00
20	0.000E+00	0.000E+00	0.000E+00	3.961E-13	1.000E+00